EFFECTS OF WIND FORCING ON SURFACE CURRENTS AND MESOSCALE EDDIES

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This thesis is submitted in fulfilment of the requirements for the degree of Doctor of Philosophy of the University of Western Australia School of Civil, Environmental, and Mining Engineering, The UWA Oceans Institute 2017
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I, Jennifer Penton, certify that:

This thesis has been substantially accomplished during enrolment in the degree.

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Abstract

Surface currents play a major role in the transport of buoyant material, distribution of contaminants, connectivity of marine populations, planning of navigational routes and in search and rescue. High Frequency Radar (HFR) provide one of few oceanographic methods that allows for the measurement of surface currents in the ocean. The HFR systems (WERA and SeaSonde), deployed along the Rottnest continental shelf (west coast of Australia) as a part of the Integrated Marine Observing System (IMOS), have been collecting data on the local surface current patterns since 2010. This data set is used to define the surface current variability in response to wind forcing along the Rottnest continental shelf region. In this micro-tidal region, wind is characterised by sea breezes and storms during summer and winter and comprises the major forcing of oceanic surface currents, particularly along the shelf. High correlations were found between surface currents and winds along the continental shelf region, where currents respond almost instantaneously (<3 h) to wind forcing. The wind effects on the surface currents are diminished in deeper water (>150 m), where the Leeuwin Current dominates. The surface current response to winds also exhibits a seasonal variability. The summer months consist of both strong sea breeze regimes and storm events with winds predominantly from a southerly direction. Persistent winds allow for more prolonged forcing on surface currents, thus driving the generation of northward currents along the continental shelf (e.g. the Capes Current). In winter, sea breezes are less frequent, and although the storms have higher wind speeds, they also have a higher variability in direction thus driving a more complex circulation pattern in surface currents. During the summer months, the wind field also influences the generation of meso-scale eddies, in particular in their initiation and spin-up. In response to strong southerly winds, the shear zone between the northward flowing Capes Current and the southward Leeuwin Current is enhanced, generating small scales structures that then evolve into persistent meso-scale (>50 km radius) anti-clockwise eddies. These eddies were trapped in the Perth canyon for several days. In the northern section of the study region, the Leeuwin Current eddies plays a major role in the circulation with establishment of clockwise and anti-clockwise eddy pairs during autumn and winter months.
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### Authorship Declaration: Co-Authored Publications

This thesis contains work that has been published and/or prepared for publication.

Chapter number and paper details are given below along with a statement of contribution for each paper.

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<td>3</td>
<td>Penton J., Pattiaratchi C.B., Mihanović, H. (in prep). Effects of wind forcing on surface current variability on the Rottnest continental shelf, Western Australia.</td>
<td>Continental Shelf Research.</td>
<td>This work was 70% by J. Penton. Penton did the majority of the research, created the majority of the figures and wrote the paper following the advice and guidance of the co-authors.</td>
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<td>4</td>
<td>Penton J., Pattiaratchi C.B., Cosoli S., Mihanović, H. (in prep). The influence of wind events on surface current structures such as mesoscale eddies on the Rottnest continental shelf, Western Australia.</td>
<td>Journal of Geophysical Research (oceans).</td>
<td>This work was 70% by J. Penton. Penton did the majority of the research, created the figures and wrote the paper following guidance of the co-authors.</td>
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<td>5</td>
<td>Penton J., Pattiaratchi C.B., Mihanović, H. (in prep). Analysis of coastal currents near the Turquoise continental shelf, Western Australia, using HF radar.</td>
<td>Ocean Dynamics.</td>
<td>This work was 70% by J. Penton. Penton did the majority of the research, created the figures and wrote the paper with guidance from co-authors.</td>
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**Student signature:**

Date: 5. December 2016

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I, Charitha Pattiaratchi certify that the student statements regarding their contribution to each of the works listed above are correct.

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**Coordinating supervisor signature:**

Date: 5. December 2016
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Chapter 1

Introduction

1.1 Overview
Surface currents account for significant physical, chemical, and biological processes within the ocean. Whilst previous research in the area of the continental shelf off Rottnest Island, Western Australia, has documented the seasonal currents and their meanders via ADCPs, ocean gliders, satellite images, and drifters (Mihanovic et al., 2016; Mahjabin et al., 2016; Pearce and Pattiaratchi, 1999; Zaker et al., 2002), little attention has been paid to the influence of wind and its influence on the mesoscale ocean structures due either to the pointwise measurements (ADCP), limited or suboptimal spatial coverage (gliders, drifters), or poor temporal – spatial resolution (satellite images). A comprehensive study of the surface currents and their temporal and spatial scales requires in fact synoptic data with adequate time and space resolution, that can be achieved using synoptic High Frequency Radar (HFR) data. HFR systems can provide currents over domains extending 200km offshore at a resolution of 1 to 10 km in space and 10 min to 3 hours intervals, thus addressing the major limitations of other available platforms. Of the entire broad-band spectrum of resolvable phenomena, this work focuses on the influence of wind on surface currents, on the response in space and time, on the definition of the main ocean mesoscale structures, and on the impact of wind on their generation and evolution.

Specifically, the objectives of the research are the following:

1. Determine the influence of wind on surface currents along the Rottnest continental shelf and deeper water, focusing on specific wind events such as storms and sea breezes.
2. Determine the influence of wind on mesoscale eddy structures that are formed in the shear zone between the Capes and the Leeuwin Currents.

3. Define the seasonal patterns of surface currents on the Turquoise continental shelf including the northern extent of the Capes Current.

The thesis is presented as follows: Chapter 2 describes the background of the study site in the context of original research undertaken globally as well as specifically at the study site. The functionality of HFR is described and verified as accurate for the study site. Chapter 3 describes the correlation of surface currents to wind events at the study site. Chapter 4 depicts the effect of wind on the formation and maintenance of eddies as well as their seasonality. The northern extent of the Capes Current and the seasonal mesoscale current features will be described in Chapter 5, followed by a general discussion, conclusion, and inspiration for future research (Chapter 6).

Table 1.1: Summary of papers and thesis chapter

<table>
<thead>
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<th>Paper</th>
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<td>1</td>
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1.2 Contribution

This thesis is presented as a compilation of papers to be submitted to peer-reviewed research journals. Each paper corresponds to a chapter with identical content to the published/submitted work (Table 1.1). Therefore repetition of some introductory and background material was inevitable.

The work presented in this thesis is aimed to extend the overall understanding of surface current movement, the formation of eddies, and the seasonal pattern of the
eastern boundary current of the southern Indian Ocean, the Leeuwin Current. Combined with previous findings of eddy characteristics and boundary currents, this thesis will broaden the overall understandings of oceanic current systems.

1.3 Significance
Accurate understanding of surface currents, their meanders, instabilities, temporal and spatial scales, is of critical importance for a number of activities, including for instance adequate managing of navigation, plume, pollutant, and algal bloom tracking, as well as search and rescue activities, and spillage mitigation. The Leeuwin Current and its undercurrent system have been subject of many research activities (for example by Smith et al., 1991; Benthuysen et al., 2014; Godfrey and Ridgway, 1985; Feng et al., 2003; Thompson, 1984; Pattiaratchi and Woo, 2009); however, the research to date lacks the required temporal and spatial resolution and focuses only on limited aspects, neglecting for instance the importance of wind especially in the upper portion of the water column. This thesis bridges this gap and provides a detailed analysis of the response of the coastal currents off Western Australia to typical wind regimes and seasonal wind events. The formation and dissipation of eddies is also evaluated in respect to seasonality and wind effects.
Chapter 2

Background

This Chapter provides a review of the relevant literature and represents the context for the research activity object of the present thesis. Surface currents are first introduced in Section 2.1; mesoscale eddies are then described in Section 2.2, and discussed in terms of bathymetry (Section 2.3.1) and main current systems (Section 2.3.2). Seasonal variability, including storms and sea breeze events which contribute to surface current variability and the formation of eddies in the study region, are described in Section 2.4. The final Section, 2.5, covers both the functionality of HFR and the validation of the collected data at the study sites.

2.1 Surface currents
Surface currents are confined to the upper 1.5 m of the water column. This pelagic zone contains large amounts of plankton and larvae, impacting population and nutrient distribution (White et al., 2010). Even a minor change in cross-shore current flow can impact larval dispersal distances by creating or dissipating retention zones (Largier et al., 2003). These retention zones also affect the distribution of nutrients, further affecting the distribution of population or the dynamics of various pelagic species in the area. Surface wave-induced mixing can be enhanced by increased wind-driven surface currents (Jones et al., 2008), again affecting the distribution of nutrients, with impacts on the population dynamics of species of commercial interest, and hence the fishing patterns and allowances in the region. Local upwelling or downwelling are common results of wind forcing on surface currents near the coast (Gersbach et al., 1999), which again has large implications for fisheries, their fishing allowances and desired locations.
To a large extent, wind is the major driver of global and local currents (Zhao et al., 2011), which on average flow at approximately 3% of the wind velocity (Hammond et al., 1987), with the resultant surface currents consistent enough to derive wind vectors (Harland and Georges, 1994). For instance, wind-driven dynamics represent up to 67% of subtidal variability in surface currents offshore California (Kaplan et al., 2005). Events with largest wind forcing factors have been defined as translating cold fronts and small lows with scales of 100 km (D’Asaro, 1985), whilst the variability of surface currents have been found to be directly related to the variability in seasonal winds (Solabarrieta, 2015). An important phenomenon associated with wind forcing, Ekman dynamics, results in a net depth-integrated water transport at an angle of 90° to the left of the wind direction (in the southern hemisphere, to the right in the northern hemisphere), with consequent effects on transport, mixed layer depth, and water pumping (Cosmic, 1987; Halpern, 2002; Picket and Paduan, 2003; Wicket, 1967). In the study area, Ekman transport is weak, with an annual mean of 0.1 Sv (Sverdrup; 1 Sv = 10^6 m^3 s^-1), as the eastward, onshore geostrophic transport opposes, dominating in the region (Feng et al., 2003).

2.2 Eddies
Eddies are closed-type, circular or elliptical-shape circulation features with diameters from a few km to hundreds of km, and are ubiquitous in the global oceans. They develop in the three dimensions and as such they have the potential to increase bottom flow and are regarded as important energetic and vorticity balances, which form a fundamental part in describing the character of general oceanic circulation (Holland and Lin, 1975). Similar to surface currents, eddies have the capacity to alter chemical values within the water column by, for example, uplifting chlorophyll and nutrients (Aristegui et al., 1994). This fluid can then be carried out of the area of origin as the eddy translates out (Reznik et al., 1980), hence influencing the distribution of commercially important species such as e.g. pygmy humpback whales (Rennie et al., 2006). Eddies also support vertical mixing and increase the depth of the mixed layer (Rao et al., 1989); in regions where inertial frequency is present, eddies can modulate or even block the inertial band when eddy vorticity is particularly intense (Perkins, 1976).

A number of mechanisms have been identified for the formation of eddies, including for instance: barotropic instability (Holland and Lin, 1975); river outflow (Zhao et al.,
2011); and, major wind reversals (Paduan and Cook, 1997). Contradicting findings, stating wind to have a negative (Halverson, 2013) or a positive effect (Aristegui et al., 1994) on the build-up of eddies, has increased curiosity in local wind-driven effects.

Various research, observations, and models of mesoscale, cyclonic and anti-cyclonic, warm-core eddies have been undertaken in this region (Rennie et al., 2007; Fang and Morrow, 2003; Cresswell and Golding, 1980; Feng et al., 2007; Griffiths and Pearce, 1985; Kennedy Jr, 2002; Morrow et al., 2003; Holland and Lin, 1975; Waite et al., 2007). Driving factor for eddies within the study site are either meanders of the Leeuwin Current, shelf topography, bottom shear, or barotropic instability. These eddies are often paired with cold-core eddies (Griffiths and Pearce, 1985), however insufficient attention was focused on their climatology and origin, on the role of wind and weather at the time of their formation, and on the advection of Capes Current waters in their centres. Eddy pairs have been accounted for as a result of density fronts and buoyancy-driven boundary currents (Griffiths and Pearce, 1985). This research focuses in particular on this aspect, along with the influence of local bathymetry on the formation of eddies in the region.

2.3 Local setting
The study area is located on the southwest coast of Western Australia (Figure 1). It is a micro-tidal region in which tidal forcing (at a mean spring range of 0.6 m) represents only a small fraction of the energy in both currents and sea level (Pattiaratchi and Eliot, 2009). Coastal processes along the southwest coast, including circulation, mixing, and particulate resuspension, are predominantly wind-driven (Zaker et al., 2007; Verspecht and Pattiaratchi, 2010). There are three dominant wind seasons that represent 81% of all wind conditions observed along this coastline, the remaining 19% are explained by irregular and random events (Steedman and Craig, 1983). The 81% will be discussed in the following section along with the local bathymetry and current systems.

2.3.1 Bathymetry
The bathymetric features of the region (north of Rottnest Island) are presented in Figure 2.1 and include (1) a shallow inshore region, with depths of <10 m, may be defined as a coastal lagoon with a line of discontinuous, submerged limestone reefs; (2) an upper continental shelf terrace located between ~10 km to ~40 km offshore with
a gradual slope and a mean depth of ~40 m; (3) a transition area in which depth changes rapidly from 50 m to 100 m isobaths; and, (4) the shelf break, located at ~200 m isobath at ~30 km to ~40 km offshore (Pattiaratchi, et al. 2011; Figure 2.1). The local distinctive bathymetric feature known as the Perth Canyon is also shown in Figure 2.1; it drops from the 200 m isobath, west of Rottnest Island, down to 1000 m within only 6.5 km. Bathymetric features of the region have numerous biological consequences. For example pygmy blue whales use the canyon as a feeding area in the summer months, as it enhances both pelagic production as well as physical aggregation of plankton, making it an important ecological feature of this coast (Rennie et al., 2006).

2.3.2 Currents
The circulation off the west Australian coast is different from that off other western continental margins (Smith et al., 1991). In each of the main ocean basins, the surface circulation forms a gyre with a poleward flow along the western margin of the basin and a gyre with an equatorward flow along the eastern margin. Circulation along the western coast of Australia is governed by the so-called Leeuwin Current system, which includes the Leeuwin Current, the Leeuwin Undercurrent, and the Capes Current, flowing in opposite directions at different depths (Woo and Pattiaratchi, 2008; Pattiaratchi and Woo, 2009). In this thesis the focus is on surface currents, hence the emphasis will be on the Leeuwin Current and the Capes Current, which are the current streams closest to surface. The Leeuwin Current is a warm (average temperature at surface 20.8°C), low-salinity (average salinity at surface 35.2 PSU; Feng et al., 2003), as it transports tropical waters from the Indonesian Throughflow (Smith et al., 1991). Meanders have been documented to form along the edges of the Leeuwin Current, which either break off and move offshore, or lead to large diversions of the southward flow (Pearce and Griffiths, 1991). These meanders can have a significant impact on larval dispersal and species distribution (Caputi et al., 1996). Pearce and Pattiaratchi (1998) found that the Leeuwin Current weakens during the summer months (November to March) when the southerly winds increase in frequency and intensity. Feng et al. (2003) also showed that this current intensifies during “La Nina” events. Concurrently with the summer weakening of the Leeuwin Current, the wind-driven, equatorward Capes Current flowing along the continental shelf in water depths of approximately 50 m tends to strengthen, thus displacing the Leeuwin Current offshore
The Capes Current plays an important role in the dynamics of species distribution within the area: combined with the Ekman driven transport, it is responsible for the complete flushing of the upper continental shelf up to nine times per summer (Gersbach et al., 1999). Capes Current originates from upwelling events occurring off of Cape Mentelle (Gersbach et al., 1999). The exact extent of the Capes Current to the North is still not well defined, as it may vary depending on wind variability. The source of the Capes Current explains the characteristics of the current, being cooler temperature (average temperature 19.6°C) and having higher salinity (average salinity 35.8 PSU; Gersbach et al., 1999) than the Leeuwin Current.

Figure 2.1: Map of the study site (Rottnest shelf region). The blue arrows on the shelf region correspond to the cooler, northward flowing Capes Current on the shelf, while the black arrows depict the warmer Leeuwin Current flowing southward further offshore. Details of the local bathymetry (in m) are also provided.
2.3.3 Storms
Wind has a high impact on current flow variability in the sub-tidal frequencies (Zhao et al., 2011), especially in areas of low tidal energy such as at the study site. Three dominant wind patterns explain 81% of wind variability, and they include low pressure storm systems (28%), high pressure calm periods (18%) and sea breeze events (35%) (Steedman and Craig, 1983). The remaining 19% are categorized as irregular wind patterns. Storms of 1 to 5 days duration occur all year (annual occurring 15 to 30 times on average), most frequently during the winter months (June to August; Gentilli, 1971). Along the coast of Western Australia, winter storms show a pattern with north/northeasterly winds for 12 h to 52 h, followed by a period of similar duration when winds turn into south/southwesterly, with no prevailing direction dominating for the duration of the storm. The research conducted in this thesis focuses on a number of winter storms that were selected based on their duration, strength and, most importantly, on radar data availability. The selected winter events were most prominent in July and had wind speed gusts up to 20 m/s, and are further related to as “typical winter storms” given the above described pattern.

Typical winds are generally from the south in summer, in contrast, no prevailing direction is found in winter during storm or non-storm events (Chapter 3). The prevailing southerly winds in the summer months can be based on both the local sea breeze (section 2.3.4) and summer storms, that generally last from 24 h to 36 h and are characterised by southerly winds of up to 25 m/s. Summer storms of ideal duration (>24h), force (>20 m/s), and data availability, and hence selected for analysis in this thesis, were primarily found in the month of January. These storms are further related to as “typical winter storms” given the above described pattern.

During autumn and winter (March to August), high-pressure systems are common, lasting 1 to 15 days. Easterly winds, with low wind speeds (<5 m/s), were observed during these very calm periods between the passage of low pressure fronts (Steedman and Craig, 1983).

2.3.4 Sea breeze
Sea breezes occur on two thirds of the world’s coastline, most commonly in tropic and sub-tropical regions (Masselink and Pattiaratchi, 1998). The effects of sea breezes on surface currents are frequently masked by high wave energy and large tidal ranges
However, in the Western Australia region where tides are negligible, they are an important contribution to wind-driven currents.

The diurnal Land-Sea-Breeze (LSB) system off the Western Australian coast is among the globally strongest (frequently >10 m/s with maxima reaching 20 m/s) and most consistent sea breeze regimes, resulting from a combination of forcing through the synoptic system and the land-sea temperature gradient (Pattiaratchi et al. 1997; Masselink and Pattiaratchi, 2001). Temperature differences between land and the sea drive the sea breeze system and typically result in low offshore wind speeds in the morning (around 5 m/s) when the temperature differences are minimal. By late morning/early afternoon the wind speeds increase steadily due to the increasing temperature difference between the land and sea. The sea breeze reaches a maximum (10 m/s to 15 m/s) by early/mid afternoon and subsequently decreases in magnitude overnight. The development of an onshore trough on the west coast due to warm air rising from central Australia influences the intensity and direction of the sea breeze (Kepert and Smith, 1992), and location of the trough offshore may delay the sea breeze or inhibit it entirely. The shore-parallel southerly sea breezes are considered the main acting wind force during the austral spring and summer months (September to March). The typical frequency of sea breezes in the region is 200/year. The sea breeze is stronger in the spring and summer months, and occurs daily almost two thirds of the year (Masselink and Pattiaratchi, 2001). These southerly winds and sea breezes account for approximately 35% of all wind conditions annually (Steedman and Craig, 1983). The local sea breeze is considered to be one of the world’s most energetic systems as it regularly exceeds 10 m/s, averaging at 8 m/s (Masselink, 1997; Masselink and Pattiaratchi, 2000). Influence of the sea breeze was documented up to 100 km offshore (Rennie et al., 2006); this thesis will further study the offshore and depth extension of sea breezes on currents.

2.4 Surface currents sensing from HFR
Surface currents can be defined as the currents within the top ~1 m of the water column. As they quickly (<3 h, Chapter 3) respond mostly to wind forcing, they can differ significantly from the current directions along the water column. Based on the forcing mechanisms, three general classes of surface currents can be identified: density gradient-driven currents; wind-driven currents (directly produced by wind stress on ocean surface, frequently resulting in inertial oscillations as described by Pollard and
Millard, 1970); long-wave induced currents (GOOS, 2011). A number of methods are used to measure ocean currents, including Lagrangian-type instruments (such as drifting buoys), Eulerian-type instruments (current meters on moorings), ship drift or remote sensing. Each measuring technique has intrinsic limitations and resolves a limited scale: uneven drift characteristics (drogues), no agreed standard of measurement (ship drift), and no spatial representation of measured currents (moored buoys). HFR techniques on the other hand offer both spatial and temporal measurements of surface current vectors at high temporal and spatial resolution, allowing for the differentiation of eddies, as well as large- and small-scale surface current patterns. HFR systems can also measure wind direction on the same grid as currents, and directional/non directional wave parameters on a limited grid from the lower-energy second order spectrum peaks. Though a two-way wave-currents interaction is often documented, these are not accounted for in this thesis. All data shown in this thesis is in UTC +8, Australian Western Standard Time (AWST), local time zone of data collection points.

2.4.1 Functionality
HFR systems measure surface currents through the Doppler Effect, which is the frequency offset between a signal transmitted to the ocean and its reflected component after it is backscattered by ocean waves. Backscatter signal is maximized when reflection occurs from ocean waves possessing exactly half the wavelength of the transmitted signal, which are referred to as the so-called Bragg-matching waves. Frequencies of 3 MHz to 30 MHz are applied depending on the desired achievable range, the spatial resolution, and the typical wave climate in the region of interest. Lower frequencies allow for higher ranges (up to 200 km) but reduced spatial resolution (Gurgel et al., 2000). Figure 2.2 depicts the principles of this procedure, giving examples for advancing waves both with and without underlying currents.
Figure 2.2: Principle operation of HFR, from Harlan and Georges (1994).

The physical mechanism behind HFR is known as Bragg resonance. When radio waves are scattered from sea waves having half the radio wavelength and propagating either directly towards or away from the radio source, the scattered radio waves constructively interfere producing a large signal; they are also Doppler shifted in frequency. Two "Bragg lines" appear in the Doppler frequency spectrum of returned echoes (Figure 2.2). The frequencies at which the lines appear are related to the phase velocity of the advancing and receding sea waves. If there is no current, the lines are symmetrical about the zero Doppler shift. If the water surface over which the sea waves are travelling is also moving, however, then the two Bragg lines are displaced from their normal positions by an amount proportional to the component of the surface current in the direction of the radar. Two radar systems are required to reconstruct the vector component on a regular grid in an area where the two radars overlap, provided some geometrical constraints are satisfied.

The quality of these measurements, according to Chavanne et al. (2010), depends on two parameters: (1) conditions in which the signal propagates; (2) the ambient electromagnetic noise. A diurnal pattern was found, in which ranges of 50% data
return was 25% larger during the day than during the night. Chavanne et al. (2010) explained this variability in terms of various layers of the ionosphere and their dissipative and reflective traits. A dissipative layer is present during the day, inhibiting the propagation of electromagnetic signals. This layer disappears during the night and allows for the more reflective layer to support the propagation of the distant electromagnetic signals, for example those of the HFR. Due to these layers, similar diurnal data variability is also found within HFR observations in the Rottnest shelf region. External interferences also limit the usable data in the region.

Two types of HFR are used to collect the data for the Perth coastal region (and presented in this thesis):

1. WERA (WEllen RAdar) radar, which is a phased array radar system with a 4 element antenna array transmitter and a 16-element antenna receiver system. The radar setup at Leighton Beach (Figure 2.3) and Guilderton functions at 8.5125 MHz and has a wavelength of approximately 35.2 m, a spatial resolution of 4 km and an operative coverage of approximately 140 km by 100 km.

2. CODAR (Coastal Ocean Dynamics Application Radar) radars are compact systems with a single transmitter element and a single receiver element. The radar setup along the Turquoise shelf transmits at 5.2115 MHz with a wavelength of approximately 57.5 m. The grid resolution is 5 km and extends approximately 150 km by 175 km.
In order to achieve accurate vector surface current estimates, current data must be combined from two or more sites. In order to avoid inaccurate data, which will occur when both sites measure the same data, a Geometric Dilution of Precision (GDOP) is computed following Chapman et al. (1997; Figure 2.4 and 2.5). The ideal GDOP at this location, was calculated following Shay et al. (2007), with intersection angles set to $30^\circ < 2\Theta < 150^\circ$. Combining the quality control and the GDOP values, the total acceptable data points were reduced to 1037 (Figure 2.7) of the overall 5704 data points that were available (Figure 2.6).
Figure 2.4: Schematic of the Geometric Dilution of Precision (GDOP) constraint for a two-systems radar (Chapman et al., 1997)

\[
\sigma_n = \left[2 \left( \frac{\sin^2 \alpha \sin^2 \theta + \cos^2 \alpha \cos^2 \theta}{\sin^2(2\theta)} \right) \right]^{1/2} \sigma
\]

\[
\sigma_e = \left[2 \left( \frac{\cos^2 \alpha \sin^2 \theta + \sin^2 \alpha \cos^2 \theta}{\sin^2(2\theta)} \right) \right]^{1/2} \sigma
\]

\(\sigma_n\) = North component of GDOP  
\(\sigma_e\) = East component of GDOP  
\(\alpha\) = Mean look angle  
\(\theta\) = Half of the angle of intersecting beams  
\(\sigma\) = rms (root mean square) current differences

Figure 2.5: Equation for the calculation of the GDOP errors for the current velocity components (Chapman et al., 1997)
Figure 2.6: Percent data return for the WERA radar systems along the Rottnest Shelf region, color-coded based on the data availability (warmer colors indicate higher data availability)
Figure 2.7: As above, but with standard GDOP limits applied. A threshold of 15% data return is also applied. Overall 1037 GDOP acceptable points were determined as accurate for this location by Mihanović (2011).

2.4.2 Verification of HFR surface currents

The data of the Australian coastal ocean radar network, from which the data for this study was taken, undergoes operational management procedures before it is released (Middlesditch and Cosoli, 2016). These quality control procedures are applied at three different levels, described as Levels 0 (Doppler spectra), 1 (radial currents), and 2 (vector currents). The ACORN systems apply 60 minute temporal averaging at Level 0 to ensure uniform processing of current measurements. Additionally, in Level 0, software (Seaview Sensing) is used to convert the beam-formed power spectra into the radial components. The Doppler spectra is then filtered to uphold quality thresholds, such as the removal of the carrier signal. Level 1 procedures, aimed at optimizing the
radial currents, are based on either pre-defined diagnostic variables or statistical properties of the data. These procedures include but are not limited to a Median Absolute Deviation filter, a First-Difference filter, and a Radial Velocity Distribution filter (see Middleditch and Cosoli (2016) for further details). Level 2 procedures, such as a Reference Signal filter, are applied to optimize the vector currents and are based on statistical properties of the data.

While HFR data accuracy has been extensively proven in various studies, data accuracy in the study area was further investigated using current data from moored current meters (ADCP) and satellite data (Mihanović, 2011). A summary is provided below:

Several data sets were collected from buoys offshore of Perth (Figure 2.8), all showing high values of correlation between the HFR data and the ADCP data (example of this given in Figure 2.9 and Figure 2.10). After having confirmed localized agreement of current vectors between data sets, a large scale comparison was undertaken by sub plotting satellite sea surface temperature (SST) and surface chlorophyll (SSC) measurements beneath the HFR surface current measurements (Figures 2.11 & 2.12). These clearly showed the movement of the cooler northbound Capes Current with its higher chlorophyll values, as well as the warm southbound Leeuwin Current. Having verified the HFR data with two independent data sets, it was concluded that the archived HFR data was accurate and was deemed satisfactory to be processed and analysed in this study.
Figure 2.8: Map of the study site (Rottnest shelf region). Capes Current (blue) and Leeuwin Current (red) are depicted. Details of the local bathymetry (in m) are also provided. The black squares show the locations of the mooring chains. Black dots indicate the locations of the HFR systems, black inverted triangle indicates the location of the meteorological station.
Figure 2.9: U and V components of ADCP and WERA HFR surface currents.

Figure 2.10: Low pass filter of ADCP and WERA HFR current data.
Figure 2.11: SST and SSC images under HFR current data.

Figure 2.12: SST and SSC images overlain to daily-averaged HFR current data for 17th March, 2010, and for 30th November, 2010.
Chapter 3

Effects of wind forcing on surface current variability along the Rottnest continental shelf, Western Australia

3.1 Summary
Surface currents play a major role in the distribution of contaminants, connectivity of marine populations, planning of navigational routes, and can influence the vertical and horizontal distribution of nutrients within the water column. In coastal regions where tidal forcing is negligible, such as the Rottnest shelf region, wind is one of the dominant forces which may interact with the large-scale, low frequency shelf current systems. This chapter aims at determining the response of surface currents to wind events on the continental shelf/slope surrounding Rottnest Island, Western Australia, focusing in particular on the role of sea breeze winds and the seasonal storm events on low-frequency, non-tidal surface current component. For all the examined wind events, significant correlation was found between wind and surface currents, particularly in the shelf region. Seasonal averages revealed strong correlation between the southerly winds and the Capes Current system, which are characteristic for the spring and summer months.

3.2 Introduction
Understanding the behaviour of surface currents (top 1.5 m layer of the water column) on the continental shelf and in offshore regions is important for a range of oceanographic applications such as, navigation, dispersal of marine populations, debris, nutrients and pollutants, and search and rescue operations. This top layer contains large amounts of buoyant plankton and larvae, impacting population and nutrient distribution (White et al., 2010) as well as floating debris such as plastics (Reisser et al., 2015). Surface current fields can be used to calculate drift trajectories and offer critical information for coastal management and emergency response. For example, surface current field can be used to predict where and when drifting material
will reach the shore. Even in regions where tidal forcing accounts for most of the current energy, wind still plays an important role in the dynamics of the surface current field. Hammond et al. (1987) showed that residual currents at the sea surface in Swansea Bay are strongly influenced by wind forcing, in spite of the 10 m tidal range. This is a common feature in many coastal areas (Zhao et al., 2011; Ursella et al., 2006; Gačić et al., 2009; Harland and Georges, 1994). In California, 67% of subtidal variability in surface currents is accounted for by wind-driven dynamics (Kaplan et al., 2005). Events with highest wind forcing factors have been defined as translating cold fronts and small low pressure systems with scales of 100 km (D’Asaro, 1985), whilst the variability of surface currents have been found to be directly related to the variability in seasonal winds (Solabarrieta, 2015). Prandle et al. (1991) referred to water regions affected by wind as “slabs”, and implied that the currents within a slab aligned to the wind, and concluded that the variability of current vectors within these slabs may suggest a variation of slab thickness. Impacts of strong wind events on surface currents commonly form mesoscale structures such as eddies and gyres (Poulain et al., 2001). Based on documented data and modelling results, it has been found that wind events can cause current reversals (Orlić et al., 1994; Poulain et al., 2004) that could lead to strong shear zones in the vertical and in the horizontal dimension of the water column. It is generally assumed that in small-scale flows, where the effects of Earth’s rotation (Coriolis force) may negligible, the surface current speed is up to ~3% of the wind speed and generally flow in the direction of the wind (Prandle et al., 1991; Hammond et al., 1987).

Surface current measurements are rarely collected over large areas or at synoptic scales with adequate resolution in space and time. Majority of current data are collected from either transects or single locations (through Lagrangian drifters, or moorings) or via satellites, but they either lack the resolution in the upper column, have a sparse coverage, or a coarse resolution. Based on their design, some drifters are more susceptible to wind-based bias, resulting in biased current measurements. Moored data only represent single locations and often cannot obtain data close to the ocean surface due to presence of waves or high tidal ranges which cause changes in water level. However, High Frequency Radar (HFR) systems allow us to overcome these difficulties and provide maps of surface currents over a large surface area at high temporal resolution.
This Chapter uses surface current data derived from HFR together with meteorological data to examine the role of wind forcing on surface currents along the Rottnest continental shelf, southwest Western Australia. Varying intensities and duration of wind events allow for a comprehensive investigation of the effect of wind on surface currents under various scenarios. In particular the following are examined:

(1) Seasonal variability of wind and its role in driving surface currents on the continental shelf and offshore region;
(2) Response and spatial extent of the wind-to-current variability driven by the sea breeze regime;
(3) Response of surface current field to characteristic seasonal wind events, such as winter and summer storms.

The study site, with its low tidal range and abundance of distinct events with unique characteristics (storms and sea breezes), represents an ideal setting to undertake the study of the effects of wind on surface currents. The offshore extent of the sea breeze and its effect on surface currents will be examined. Furthermore, the effect of storm events will be taken under examination, analysing the correlation of the surface currents to these events, offering new insights into response of shelf and offshore currents to wind forcing. This will allow for better understanding of the currents on the continental shelf and will provide aid in the complex ventures of navigation, pollutant tracking, and search and rescue in this region.

This Chapter is organized as follows: Section 3.2 provides an introduction to the subject. The study area is described in Section 3.3, including facts on seasonal winds, sea breeze, local currents and bathymetry. Section 3.4 depicts the methods of data and analytical techniques, leading to results in Section 3.5. Results are organised by event type, beginning with winds, seasonal variability, summer and winter storms, and finally sea breeze regime. Section 3.6 discusses the results of each wind event and Section 3.7 renders concluding remarks.
3.3 Study area
The study area is located on the southwest coast of Western Australia (Figure 3.1). It is a micro-tidal region in which a tide with a mean spring range of 0.6 m represents only a small fraction of current and sea level variance (Pattiaratchi and Eliot, 2009). Coastal processes along the southwest coast, including circulation, mixing, and particulate resuspension, are predominantly wind-driven (Zaker et al., 2007, Verspecht and Pattiaratchi, 2010). The strong southerly winds also contribute to upwelling during the summer months (Gersbach et al., 1999). There are three predominant wind seasons that represent 81% of all the local wind conditions along this coastline: sea breeze (35%); low pressure storm systems (28%); and high pressure calm periods (18%), with the remaining 19% being categorized as irregular wind patterns (Steedman and Craig, 1983).

3.3.1 Seasonal winds and sea breeze
During winter season (June to August), the region is frequented by storm events; during summer and spring (September to February), daily sea breezes with southerly winds up to 15 m/s dominate (Masselink and Pattiaratchi, 2001a), which drive diurnal variability in the currents and vertical stratification cycle (Zaker et al., 2002; Gallop et al., 2011). Summer winds, commonly associated with sea breezes, act similar to storm events, with speeds reaching up to 20 m/s. Selected storm events are long term, observed in summer and winter, persisting at each site for 1.5 to 3 days; the storms had peak wind speeds up to 30 m/s with southerly winds in summer and northwesterly in winter.

Diurnal sea breeze wind regime occurs along two thirds of the world's coastline, especially in the tropics and subtropics (Masselink and Pattiaratchi, 1998). Strong sea breezes have been shown to support the creation of wave-driven shelf currents, and can lead to an increased average alongshore current (Pattiaratchi et al., 1997; Gallop et al., 2011 for instance reported current flow intensification from 0.05 m/s to 1.0 m/s). The Rottnest shelf is affected by one of the strongest and most consistent sea breeze systems on earth with ~200 sea breeze events per year. They occur more frequently and with higher intensity in the summer months (Pattiaratchi et al., 1997). In southwestern Australia, sea breezes differ from the ‘typical’ sea breezes observed elsewhere, which usually blow perpendicularly onshore. The sea breezes in this study region tend to blow parallel to shore (in a north-south direction) due to the interactions
with geostrophic winds from the synoptic weather patterns (Pattiaratchi et al., 1997). The decomposition of the measured winds at Rottnest Island to high frequency (<36 h) and low frequency (>36 h) components suggested that that the high frequency component of the wind, representing the sea breeze system has a predominant south-west to north-east direction, oriented ~45° counterclockwise from the east (Mihanović et al., 2016). The low frequency component revealed predominately southerly winds representing the synoptic condition that dominates the wind system. The average sea breeze starts at approximately 14hr and blows approximately until 21hr with an average velocity of 5.7 m/s (Masselink and Pattiaratchi, 2001). The land breeze occurs at night blowing offshore and typically has speeds of 5 m/s or less (Masselink and Pattiaratchi, 1998).

Winter storms and fronts occur typically most frequently in July (Gentilli, 1971). During the passage of a frontal system, the region is subject initially to northerly winds which shift to north-westerlies of 25 m/s up to 30 m/s. Winds then change direction from west followed to southwest over 12 h to 16 h as the system crosses the coast (Lemm et al., 1999; Masselink & Pattiaratchi, 2001). Generally, the southwesterly winds gradually weaken over two to three days, and calm, cloud-free conditions prevail for another three to five days before the passage of another frontal system.

3.3.2 Local currents
The typical pattern of the ocean currents along WA’s coast are driven by the southbound Leeuwin Current and its counter current, the Capes Current, which flows equatorward on the shelf during the austral summer (Woo and Pattiaratchi, 2008; Figure 3.1).
The Leeuwin Current is a warm (average temperature at surface 20.8°C), low salinity (average salinity at surface 35.2 PSU) eastern boundary current that flows southward along the edge of the continental shelf (Feng et al., 2003). It transports tropical waters originating from the Indonesian Throughflow, and flows strongest during the austral autumn and winter months (April to September) when the opposing southerly (sea breeze) winds are weakest (Smith et al., 1991).

The Capes Current flows equatorward along the coast inshore of the Leeuwin Current (Pearce and Pattiaratchi, 1999). It is generated during the summer months due to localised upwelling of cooler waters approximately at 34°S (Gersbach et al., 1999). This cooler water (average temperature 19.6°C) flows on the inner continental shelf,
which extends approximately 20 km offshore and has typical depths of 50 m, broadening as it moves from 34°S northward of Perth. It is also higher in salinity (35.8 PSU; Gersbach et al., 1999) than the Leeuwin Current, and it intensifies in the summer/spring season when wind conditions are dominated by southerly winds and sea breezes (Pattiaratchi et al., 1997). From November to March, winds are prevalently northwards, pushing the Leeuwin Current offshore and reinforcing the Capes Current.

3.3.3 Bathymetry
The study region includes Rottnest Island (Figure 3.1), which forms a physical barrier to water transport along the shelf. To the north of the Island, an upper continental shelf terrace is located from ~10 km to ~40 km offshore with a gradual slope and mean depth of ~40 m. Seaward of this terrace, between 50 m and 100 m isobaths, the depth increases rapidly with the main continental shelf break located at ~200 m isobath. The Perth Canyon is located to the west of Rottnest Island, and drops from the 200 m isobath down to 1000 m within only 6.5 km (Figure 3.1).

3.4 Methods
HFR data offers an adequate and accurate coverage of this large study site (approximately 140 km by 110 km), at high resolution in space (4 km) and time (hourly data over a 4 year period) making this data set and region the ideal case study.

3.4.1 Data
Data were collected at the Rottnest Island region from March 2010 till March 2014 (4 years). Surface current data were in the region were made available through the Australian Coastal Ocean Radar Network (ACORN) facility, which is part of the Western Australian Integrated Ocean Observation System (WAIMOS). Surface currents were measured using a phased array Wellen Radar (WERA), which is a non-invasive, environmentally friendly, shore-based system. The HFR systems, located at Leighton Beach in Fremantle and at Guilderton, north of Perth (Figure 3.1), were set at a frequency of 8.5125 MHz and a bandwidth of 33 kHz, providing ocean currents with spatial resolution of 4 km. Note the variation in the spatial coverage of the radar domain in selected figures (e.g. Figure 3.3a compared to Figure 3.3d): this is primarily due to the availability of data (e.g. due to variation in the height of the ionosphere, the offshore range is reduced).
Meteorological data were collected at the Rottnest Island weather station (32.0069°S, 115.5022°E), 10 km to 30 km from the Perth Canyon sites (Figure 3.1). Wind speed and direction were recorded at a height of 10 m above the ground, every 30 min. These were interpolated and re-sampled into 1h-intervals to correspond with radar data. All depicted data is in AWST.

### 3.4.2 Analytical techniques

The HFR surface current data were downloaded from the IMOS data portal ([www.imos.org.au](http://www.imos.org.au)). The data available on the portal is quality controlled using post-processing software developed by ACORN, the IMOS HFR Facility. This software included an analysis algorithm to step from raw spectra to surface current components and provide meaningful quality control flags on the data points (Heron and Prytz, 2011). Spurious data (i.e. those with high velocities >2.0 m/s) were removed and, where possible, were replaced with spatially and/or temporally interpolated data points. The resulting data sets data were analysed using MATLAB with the analyses focused on the variation of current vectors in response to the sea breeze and various storm conditions.

The data analyses were conducted over the 4 year period of March 2010 to March 2014. Initially, analyses were performed on HFR surface currents and wind data separated into Austral seasons (winter: June to August; spring: September to November; summer: December to February; autumn: March to May). Then, particular events were analysed: summer storms (19th to 24th January, 2011; 17th to 21st January, 2013), winter storms (27th to 31st July, 2012; 23rd to 25th July, 2013), and sea breeze events (31st March to 3rd April, 2011; 18th to 21st December, 2013). These periods represent typical wind events for this region and were chosen based also on the availability of HFR data. Other storms with more severe wind conditions occurred during the 4 years, however HFR coverage was intermittent and not adequate to support analysis. Analysis methods included complex correlation, computed using the technique originally performed by Kundu (1976) and reapplied by Graber et al. (1997), where the magnitude and phase of the complex correlation coefficients of the wind and surface current time series \((w_1(t) = u_1 + iv_1)\) and \((w_2(t) = u_2 + iv_2)\) were calculated as

\[
\rho = \frac{\langle w_1 w_2^* \rangle}{\langle w_1 w_1^* \rangle^{1/2} \langle w_2 w_2^* \rangle^{1/2}}
\]
where $u$ and $v$ are the east-west and north-south components, the asterisk denoting the complex conjugation.

Main focus was on the magnitude of the complex coefficient $\rho$, a measure of the vector correlation between winds and currents. The phase angle was also considered as it describes the counterclockwise veering of the second vector (currents) in respect to the first vector (wind).

In order to determine the presence of time delays between winds and currents, temporal lag up to 3 h was considered and correlations were computed at lags $t = 0$ h, 1 h, 2 h, 3 h. Results of the time lag correlation analyses however showed that there was no statistically significant delay in the response of currents to winds for long-term time scales (i.e. seasonal scale), as well as single wind events with duration of up to 24 h, such as sea breeze events (Figures 3.2 and 3.3 respectively). The general correlation patterns remained the same, indicating that the behaviour of surface currents in respect to the wind was location-related rather than lag-related. This confirms the findings of Gallop et al. (2011) who, using ADCP velocity profile data along the inner shelf of the study region, demonstrated that the whole water column responds to wind forcing with negligible lag. All further correlation calculations within this paper are hence presented at zero lag.

Time series of current vectors were extracted from two cross-shelf transects located to the north and south of Rottnest Island (Figure 3.1) for each of the selected wind events.

As described in section 3.2, the seasonal wind patterns and storms are distinct, and sea breezes are a common event in the study region. To confirm the seasonality of local wind patterns, seasonal wind rose plots were created based on the 4 years of available data. Two examples each were then specified for summer storms, winter storms, and sea breezes. The two chosen summer storm events have a temporal duration of 5 days each. These were then more closely analysed at periods of 24 h and 60 h respectively, offering various time scales and intensities. Both events were additionally analysed at 24 h and 8 h means using complex correlations, focusing on time-based variations of correlations. The sea breeze events were chosen based on their intensity and consecutive rotations of wind vectors, offering consecutive sea breeze events over 3 days in both cases. These 72 h periods were more closely analysed by examining 24 h,
a singular sea breeze event, which was divided into 4 h intervals in order to produce current vector maps. Complex correlation analyses were then performed for 24 h and 8 h means. As all wind events, winter storms were selected based on their quality and quantity of radar and wind data available, offering two events of 5 days, which were analysed in 12 h sections to produce surface current vectors, and 24 h as well as 8 h means to produce time-of-day-specific complex correlation plots.

Table 3.1: Summary of average characteristics of chosen wind events: Summer storm, winter storm and sea breeze.

<table>
<thead>
<tr>
<th>Wind event</th>
<th>Direction</th>
<th>Duration of analysed data</th>
<th>Typical maximum wind velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer storm, 2 events selected</td>
<td>Southerly</td>
<td>5 days per event</td>
<td>25 m/s</td>
</tr>
<tr>
<td>Winter storm, 2 events selected</td>
<td>North/north westerly to south/south westerly</td>
<td>5 days per event</td>
<td>20 m/s</td>
</tr>
<tr>
<td>Sea breeze, 2 events selected</td>
<td>East/north easterly to southerly</td>
<td>3 days per event</td>
<td>20 m/s</td>
</tr>
</tbody>
</table>
Figure 3.2: Summer (a,b), autumn (c,d), winter (e,f), spring (g,h) correlations between wind and currents with 0, and 3 h lags (left and right columns respectively). Images suggest no significant differences for all seasons, though during spring higher correlation was found at 3 h lag. This variation was nevertheless not statistically significant.
Figure 3.3: two sea breeze events (top (a, b) and bottom (c, d)) correlations between wind and currents with 0, and 3 h lags (left (a, c) and right (b, d) columns respectively)
3.5 Results
Based on HFR data, the results described in this section depict seasonal and wind event-specific patterns of surface current movement in the study area. Seasonal wind results allowed for the focus to be put on sea breeze events, summer and winter months, to analyse the wind-driven evolution and characteristics of surface currents.

3.5.1 Winds
In order to confirm previous observations, an analysis of the local seasonal wind patterns was undertaken, confirming seasonal variability.

The mean winds of each season over the 4 year study period indicated southerly winds to be the most prevailing in summer, autumn and spring, followed by south/southeasterly winds (Figure 3.4). The southerly winds of the summer months can be largely attributed to summer storms, which are characterised by strong southerly winds of up to 25 m/s, lasting typically 36 h. Sea breeze events usually contribute to southerly winds, reinforcing the prevailing southerly winds found in the seasonal rose plots (Figure 3.4). Autumn shows preference to southerly winds with less velocity (13 m/s) than in summer. The winter months showed no prevailing wind direction, reflecting the typical winter storms, which display a rotation of wind. Spring is characterised by southerly winds of an average of 15 m/s.
Figure 3.4: Wind rose plots for all 4 seasons depicting variability within the wind patterns.
3.5.2 Seasonal variability
The complex correlation analysis between HFR surface currents and winds for all the seasons suggested that the highest values of the complex correlation coefficient ($\rho$) were found on the upper terrace of the continental shelf region in water depths <100 m (Figure 3.5). The correlation coefficient immediately north of Rottnest Island was persistently lower than those on the shelf. The correlation coefficients were low in the offshore deep water. The maximum correlation coefficient between wind and surface currents was found in spring, with correlation coefficient reaching $\rho=0.7$ over a large region of the shelf decreasing to $\rho=0.5$ in the Rottnest Island wake region. The high correlation strip was widest in the spring, slowly decreasing in width and magnitude through to summer, autumn and winter, in that order. Summer correlation coefficient also reached $\rho=0.7$, however typical magnitudes reached $\rho=0.6$ in the majority of the shelf region. Correlation coefficients in autumn was $\rho=0.6$ in the shelf region; a decrease down to $\rho=0.4$ can be observed northwest of Rottnest Island. Winter shows the same drop in correlation coefficient to $\rho=0.4$ north of Rottnest Island, which expands over the entire shelf strip. The maximum correlation coefficient reached in winter was $\rho=0.5$, representing the lowest seasonal average in the shallow shelf region.

During the summer season the phase shift (or angular veering) between currents and wind was 45° to the left within the shelf region. This corresponds to the Ekman dynamics with the surface currents flowing at an angle 45° to the left of the wind direction (southern hemisphere). In the offshore region, the veering angle was 180° in the region of the Leeuwin Current (Figure 3.6 b). The southbound Leeuwin Current is influenced by the southerly winds at the surface, as the winds decrease the current’s strength increases towards the south (a veering angle of 180° i.e. opposite to the wind direction). In autumn and winter, the veering angle depicted lower degrees of variation between shelf and offshore regions in comparison to the spring and summer months (Figure 3.6). Variations in the veering angle found in the vicinity of the Perth Canyon are most likely due to the presence of eddies in that region (Figure 3.6 d and e).
Figure 3.5: Wind/current vector correlations between seasonal current and wind averages, depicting variability in spring (a), summer (b), autumn (c), and winter (d).
Figure 3.6: Seasonal (spring (a), summer (b), autumn (c), and winter (d)) phase shift plots between wind and surface currents.
3.5.3 Summer storms

Summer storms, during which the winds blow continuously from the south (commonly accelerated by the afternoon sea breeze), typically last 3 to 4 days, and offer the opportunity to investigate effects on surface currents over time frames of several days. Two examples were chosen based on data availability and storm severity (based on wind direction from the south and wind velocity averaging >15 m/s): (1) from 12:30 on the 8th February through till the 10th February, 2014; and, (2) from 00:30 on the 16th January, through till the 20th January, 2013 at 00:30. The sequence of surface current maps (Figure 3.7 and Figure 3.8) suggested that the response of the currents was stronger in the shallower areas of <100 m water depth located on the shelf, where high correlation coefficients were found. In Example 1 it is shown that after 20 h of southerly winds, the offshore currents tend to align with the wind direction (Figure 3.7). Even after 24 h of strong southerly winds, as shown in the second example, the Leeuwin Current still prevails in the deeper water region.

The 6 h time steps in Figure 3.7 depict the development of the currents: a) 8th February 12:30: strong northerly currents in the shelf region, representing a strong Capes Current. Offshore currents flowing eastward; b) 8th February 18:30: strong northerly currents in the entire region; c) 9th February 0:30: northerly currents in the shelf region, westerly currents offshore; d) 9th February 6:30: northern shelf region depicts the Capes Current flowing north, the southern shelf region is dominated by westerly currents. Offshore shows a clear Leeuwin Current; e) 9th February 12:30: the Capes Current is clearly visible with the offshore currents flowing east and forming an eddy in the northern part of the study site; f) 9th February 18:30: strong northbound currents in the entire region; g) 10th February 0:30: strong southerly currents along the shelf, offshore currents have begun veering westward in the southern region of the study site; h) 10th February 6:30: clear Capes and Leeuwin Current pattern visible with a shear zone in the middle, along the outer edge of the shelf, showing small eddies throughout; i) 10th February 12:30: strong northerly currents along the shelf with weaker northerly/northeasterly currents in the offshore region.

Time series of current maps from Example 2 depicts the evolution of a summer storm with southward currents across the whole study region on 16th January, 2013 (Figures 3.8 a, b). The meandering nature of the Leeuwin Current may be identified
with higher velocities. The winds changed to a southerly direction late on 16\textsuperscript{th} January initiating the summer storm. The currents as depicted in 12 h time steps in Figure 3.8 undergo the following changes: a) southerly currents are present in the entire study site; b) 16\textsuperscript{th} January 12:30: northerly/northeasterly currents throughout the entire region; c) 17\textsuperscript{th} January 0:30: the shelf currents have turned northerly, the offshore currents are still heading south; d) 17\textsuperscript{th} January 12:30: the Capes Current is flowing strongly on the shelf and has formed a shear zone with the southward Leeuwin Current further offshore; e) 18\textsuperscript{th} January 0:30: strong Capes Current and Leeuwin Current are visible, an eddy has begun to form in the shear zone above the Perth Canyon; f) 18\textsuperscript{th} January 12:30: the Capes Current is flowing strongly, the Leeuwin Current shows weak currents in the western boundary of the region, while the shear zone is still strongly present along the outer edge of the shelf; g) 19\textsuperscript{th} January 0:30: strong Capes and Leeuwin Current; h) 19\textsuperscript{th} January 12:30: the Capes Current has been enhanced and the Leeuwin Current is flowing strongly, allowing an eddy to form in the shear zone above the Perth Canyon; i) 20\textsuperscript{th} January 0:30: the Capes Current is strongest at the boundary of the eddy, while the Leeuwin Current flows strongly offshore.
Figure 3.7: Time sequence of 6-hourly surface maps, for the summer storm of 8th to 10th February, 2014, commencing at 12:30 on the 8th of February through till the 10th of February, 2014.
Figure 3.8: Time sequence of 12-hourly surface maps, for the summer storm of 16\textsuperscript{th} to 20\textsuperscript{th} January, 2013, commencing at 0:30 on the 16\textsuperscript{th} of January, through till the 20\textsuperscript{th} January, 2013 at 0:30.

During the summer storms the complex vector correlation coefficient between wind and currents were high ($\rho>0.9$), with the correlation coefficient higher in the shelf region than offshore over a 24 h average (Figures 3.9 and 3.10). The wind was strongest in the late afternoon and night, which was reflected by the increased correlation in the offshore region for the 16:00 to 24:00 time period. Regions of no statistical significance of correlation, which are found offshore in the 24 h average, were associated with the Leeuwin Current, flowing at approximately 180° to the wind direction for the majority of the storm period. In this case, regions of low
(ρ<0.3) correlation coefficient on the shelf reflect the location of the eddy (Figure 3.10).

a)

Figure 3.9: Wind/current correlation plots of the summer storm, February 8th, 2014: 1600 to 0:00 showing extremely high correlation of up to 1 in both the shelf and offshore regions (a); 24 h average showing high correlation of 0.9 in the shelf region <100 m and correlations as low as 0.1 in the mid- and offshore regions (b) (24 and 8 data sets used respectively).
Figure 3.10: Wind/current correlation of the summer storm, January 19th, 2013: 1600 to 0:00 showing high correlation of 0.9 in most regions with exceptions in the shear zone and the location of the eddy as well as far offshore (a); 24 h average depicting high correlation in the shelf zone (up to 0.9), lowest correlations found in the shear zone and far offshore (b) (8 and 24 data sets used respectively).

Cross-shelf velocity transects allowed for a closer examination of the development of surface currents across the shelf with time. It should be noted that the offshore range
of the plots indicate a diurnal signal due to the effects of the ionosphere. The velocity transects indicated the northward shelf currents increasing in velocity with time and forcing the Leeuwin Current further offshore with time. In example 1, 8th to 13th February, 2014, the winds had a southerly component throughout but with a modulation in both speed and direction (Figure 3.11). Initially, the winds were strong from the south and changed to southeasterly on 8th February 2016 from noon onwards. On the following day the winds became southerly and stronger. Then the winds were southeasterly and gradually decreased in speed until 13th February. During this period the shelf currents responded almost instantaneously to changes in wind speed and direction. As the north component of the shelf currents increased (Figure 3.11 a), the width of the Capes Current also increased, forcing the Leeuwin Current further offshore (12:30 9th to 10th February, 2014) and then decreased as the winds decreased in speed. The southern transect indicated a similar response of the shelf currents to the wind, allowing the Capes Current to push the Leeuwin Current further offshore, as it increased in velocity. When the winds changed to southeasterly, the currents decreased in velocity and a direction towards the northwest.

In the Example 2, the winds are mainly southerly except at the beginning of the period, the winds were southeast (Figure 3.12). In both transects (north and south) the shear zone between the Capes and the Leeuwin Current is clearly defined as the Leeuwin current has higher velocities compared to Example 1 (cf Figures 3.11 and 3.12). A feature during this period was that the Capes Current strengthened with time increasing the offshore Ekman transport and forced the migration of the Leeuwin Current further offshore. This phenomenon was first identified by Pearce and Pattiaratchi (1999). The offshore migration is clearly shown on the northern transect where over the 5 day period the shear zone was shifted offshore by ~28 km. The southern transect shows a stronger response of the shelf current to the wind than the northern transect. On both transects, the Capes Current clearly increases in velocity as well as width during these periods. With both currents experiencing accelerated velocities, an increased amount of shear is present in the shear zone, generating eddies along the shear zone (Figure 3.12 b) which are discussed in Chapter 4.
Figure 3.11: Transect time plots of the summer storm, 8\textsuperscript{th} to 13\textsuperscript{th} February, 2014, along the northern (a) and southern (b) transects, depicting the intensification of the Capes Current and the offshore movement of the Leeuwin Current. The wind vectors are shown in red.
Figure 3.12: Transect time plot of summer storm, 17th to 21st January, 2013, along the northern (a) and southern (b) transects, showing a clear westward movement of the shear zone as the Leeuwin Current gets pushed offshore. Wind vectors are shown in red.
Linear correlation between the northward components of wind speed and HFR current component indicated a high correlation with currents flowing at 2.4% and 1.8% of the wind speed during the summer storms of February 2014 and January 2013 respectively (Figure 3.13).

Figure 3.13: Scatter plots of maximum of hourly V components of currents plotted over hourly V components of wind, showing a positive relation of 2.4% and 1.8% for the summer storms of February 2014 (a) and January 2013 (b).
3.5.4 Winter storms
Response of surface currents to wind forcing is more complex in winter. During a winter storm, the wind direction changes continuously in an anti-clockwise direction starting from the northeast (or north) and progressing to northwest; west and southwest over a period < 24 h. The maximum wind speeds occur when the winds are from the northwest. Example 3, from 28th to 31st July, 2012 (Figure 3.14), shows a clear divide between the deeper offshore and the shallow shelf waters throughout the entire duration of the storm. In detail, the 12 h time steps (Figure 3.14) revealed the following development of currents during the storm: a) 28th July, 12:30: currents located offshore move southwards, shelf currents show some vorticity in both clockwise and counterclockwise directions; b) 29th July, 0:30: southerly flows visible in both near and offshore with a counterclockwise spin up occurring in the middle of the study site; c) 29th July, 12:30: the uniformity of the southerly flow increases both near- and offshore; d) 30th July, 0:30: currents located offshore increase velocity and marginally veer westwards. Shelf currents flow southwards with discrepancies of westward currents west of Rottnest Island; e) 30th July, 12:30: uniform southerly flow both on the shelf and offshore; f) 31st July, 0:30: shelf currents veer eastward, whilst currents located offshore veer westward and increase in velocity.

In example 4, lasting from 23rd to 25th of July, 2013 (Figure 3.15) however, the separation of the two is only visible in the later stages of the storm. The currents located offshore, which generally flow south due to the Leeuwin Current, are accelerated throughout early phases of the storm. The waters of the shallow also flow southward, however they do not seem to reach the same velocities. In both cases, current directions have a noisy pattern, suggesting a potential build up for an eddy-like structure, which however does not fully develop. In detail, the 12 h time steps shown in Figure 3.15 depict the evolution of the currents throughout the storm as: a) 23rd July, 0:30: limited radar data indicates the intensity of the storm whilst southerly currents are visible in the covered area; b) 23rd July, 12:30: overall southerly flow with some vorticity in the north east region of the study site; c) 24th July, 0:30: offshore currents show easterly tendencies, the shelf currents also begin to turn southerly except for in the vicinity of Rottnest Island where the retain a southerly flow; d) 24th July, 12:30: shelf currents begin to show a more distinct eastward flow; e) 25th July, 0:30: currents located offshore show clear eastward flow until hitting the
shelf. Shelf currents do not show clear flow direction; f) 25th July, 12:30: counterclockwise eddy in the north of the study region begins to form. Shelf currents have aligned with the wind to a southerly flow whilst currents located offshore are yet to clearly align.
Figure 3.14: Time series of surface maps of the winter storm, 29\textsuperscript{th} to 31\textsuperscript{st} July, 2012, at 12 h intervals until the 31\textsuperscript{st} July, 2012 at 18:30.
Figure 3.15: Time series of surface maps of the winter storm, 23rd to 25th July, 2013 at 12 h intervals ending on 25th July, 2013 at 12:30.

Statistical analysis indicated the vector correlation coefficients between wind and currents to be higher in the offshore region than those found on the shelf, although $\rho > 0.5$ was determined in most regions. The main difference between the two winter storm examples (3, 4) is correlation coefficients around Rottnest Island. In Example 3 (Figure 3.16) the correlation coefficient $\rho = 0.9$, however in Example 4 (Figure 3.17) the coefficient decreases to $\rho = 0.1$ in the 16:00 to 0:00 time period and to $\rho = 0.6$ in the 24 h average. Other localised spots of low correlation can be related to currents, which neither follow the general direction of the wind nor the follow the pattern of characteristic local currents.
Figure 3.16: Wind/current correlation of the winter storm 29th July, 2012, 16:00 to 0:00 (a) and 24 h (b) (8 and 24 data sets used respectively), showing high correlations through the entire study site, with lowest correlations occurring in the southern end of the shear zone as well as on the northern shelf.
Figure 3.17: Wind/current correlation of the winter storm 23\textsuperscript{th} to 25\textsuperscript{th} July, 2013: 16:00 to 0:00 (a) and 24 h (b) (8 and 24 data sets used respectively), showing high correlations throughout the study site, with lowest correlations north of and around Rottnest Island (a and b respectively).
The cross-shelf transect plot of Example 3 (Figure 3.18) clearly indicates the intensification of the southerly Leeuwin Current throughout the storm event. The shelf currents also flow southward as the winds change from an easterly direction to northerly. Southwesterly winds occur in the final phase of a winter storm. During this phase the shelf currents followed the changing wind direction (Figure 3.18). Example 4 (Figure 3.19) illustrates an example of the degradation of an eddy, which had the offshore currents flowing northward, against the Leeuwin Current. In both examples, currents in the shallower regions responded to changes in wind direction, whereas the offshore currents were generally higher in velocity and tended to maintain their prevailing direction.
Figure 3.18: Transect time plot of the winter storm, 27th to 31st July, 2012, along the northern (a) and southern (b) transects, showing mixed shelf currents in both cases, which align with the wind as it turns northeasterly, overriding the Capes Current during northerly winds.
Figure 3.19: Transect time plot of the winter storm, 21st to 26th July, 2013, along the northern (a) and southern (b) transects, which both indicate rapid response of the shelf currents whilst the offshore currents take longer (up to 6 h) to respond to the change in wind direction.
Linear correlation between the northward components of wind speed and HFR currents indicated a high correlation with the surface currents attaining 1.3% of the wind speed during the first winter storm (July 2012; Figure 3.20). The winter storm of July 2013 however indicated no relationship between the winds and currents. It is important to note that the wind direction changed continuously throughout this period, never persisting in one direction for longer than 2 h.

3.5.5 Sea breeze regime
The sea breeze regime consists of easterly (offshore) winds during the morning and stronger southerly (shore-parallel) winds in the afternoon. Examples of sea breeze events selected indicate stronger currents offshore when compared to shelf currents. The currents generally rotated anti-clockwise in direction, with changes of intensity (Figures 3.21 and 3.22). The offshore currents show tendencies of easterly flow during the late afternoon periods, not entirely following the direction of the northward Capes Current, but also no longer clearly following the patterns of the Leeuwin Current. The sea breeze event on April 2nd 2011 (Example 5) resulted in surface current variability (Figure 3.21) as follows: a) 2nd April, 0:30: Leeuwin
Current strong and visible, some vorticity detectable in shelf region north of Rottnest Island; b) 3:30: Leeuwin Current strong, shelf currents unclear and weak; c) 6:30: Leeuwin Current persists, shelf currents show no dominant direction; d) 9:30: strong Leeuwin Current visible, offshore beginning to veer easterly; e) 12:30: Leeuwin Current veers easterly, allowing the formation of a clockwise eddy to begin; f) 15:30: clear clockwise offshore eddy at 32°S; g) 18:30: eddy is still visible; h) 21:30: offshore eddy dies down. The shelf regions react differently to the sea breeze, Example 5 showing much lower velocity than on Example 6 (19th December 2013; Figures 3.21 and 3.22 e).

The surface current vectors of the 19th December 2013 (Example 6) are shown in Figure 3.22: a) 19th December, 0:30: strong Leeuwin and Capes Currents visible, strong shear zone found between them; b) 3:30: Leeuwin Current is forced further offshore as Capes Current expands; c) 6:30: Capes Current weakens in velocity yet maintains its width; d) 9:30: Leeuwin Current and Capes Current decrease in velocity; e) 12:30: Capes Current gains velocity yet Leeuwin Current pushes further onshore; f) 15:30: Capes Current increases in velocity again, offshore clockwise vorticity visible; g) 18:30: Capes Current very strong with only a thin shear zone between it and the equally strong Leeuwin Current; h) 21:30: very strong Capes and Leeuwin Currents with narrow shear zone visible. Both cases show negative vorticity (clockwise movement) in the offshore region when the Leeuwin Current veers eastward. The major feature is the distinct separation between southward Leeuwin Current and the northward Capes Current with the presence of a shear zone between the two current systems.
Figure 3.21: Time series of surface maps of the sea breeze cycle on the 2. April, 2011, in 3 h intervals
Complex correlation coefficients between the wind and current vectors showed that different sea breeze events have different effects on the currents and their behaviour in response to the wind. The first selected sea breeze event (Example 5; April 2011, Figure 3.23) showed higher correlation offshore, the second sea breeze (Example 6; December 2013, Figure 3.24), showed higher correlations on the shelf. The sea breeze event of December 2013 also clearly shows a lack of correlation along the 100 m bathymetry line, where the shear between the Capes and the Leeuwin Currents is greatest.
Figure 3.23: Wind/current correlation plots of the sea breeze cycle 2nd April, 2011, 16:00 to 0:00 (a) and 24 h (b) (24 and 8 data sets used respectively), showing highest correlations in the offshore and mid-range region left and right respectively) of the study site, with lowest correlations found in mid region and shelf respectively.
Figure 3.24: Wind/current correlation plots of the sea breeze cycle 19\textsuperscript{th} December 2013, 16:00 to 0:00 (a) and 24 h (b) (24 and 8 data sets used respectively), showing higher correlations in the shelf area with lowest correlations in the shear zone found between the Capes and the Leeuwin Current.
The northern and southern cross-shelf transects of both sea breeze events allowed for the determination of the response of the Capes Current to the sea breeze cycle. The cross-shelf transects were affected by the ionosphere changes and thus a diurnal reduction in the offshore range of the HFR system (Figures 3.25 and 3.26). As described before, the sea breeze consists of offshore winds in the morning and southerly shore-parallel winds in the afternoon and evening (Figures 3.25 and 3.26). It can clearly be seen that there is a diurnal variation in the interface between the Capes Current and Leeuwin Current. The Capes Current is not well established (i.e. weak northward currents (Figures 3.25 and 3.26). The Leeuwin Current persists throughout the entire 3 day cycle in Example 6 (Figure 3.26), whilst in Example 5 (Figure 3.25) it is overcome and the offshore surface currents flow northbound after the sea breeze had persevered for 3 h to 12 h. Both near and offshore currents respond to a change in wind direction within 3 h.
Figure 3.25: Transect time plot of the sea breeze cycle, 31st March to 3rd April, 2011, along the northern (a) and southern (b) transects, depicting the shelf and offshore reactions of the surface currents to the sea breeze cycles, showing complete reversals of the offshore currents due to sea breeze events, verifying new extents of offshore sea breeze impacts. The wind vectors are shown in red. Note that the diurnal changes in the offshore limit of the currents is due to changes in the ionosphere.
Figure 3.26: Transect time plot of the sea breeze cycle, 18th to 21st December, 2013, along the northern (a) and southern (b) transects, depicting the shelf and offshore reactions of the surface currents to the sea breeze cycles, confirming the extents of the sea breeze into the offshore region. The wind vectors are shown in red.
Scatter plots of the V components of maximum currents over V components of wind revealed a positive relation between the two components. In Example 5 (April 2011), the ratio V(current) / V(wind) was ~1.4%, which increased to 2.0% for Example 6 (December 2013).

Figure 3.27: Scatter plots of maximum V components of currents plotted over V components of wind, showing a positive relation of 1.4% and 2% for the sea breeze events of April 2011 (a) and December 2013 (b).
3.6 Discussion
Using HFR and meteorological data, three characteristic wind events as well as seasonal averages have been examined to identify locations and periods of high correlation between the wind and current vectors within the study site. Long-term (months) high correlation coefficients were found in periods of strong southerly winds along the shelf region, where water depth doesn’t exceed 150 m. Within short-term (days) periods, such as diurnal sea breeze cycles, higher correlation coefficients were found up to the western boundary of data range, providing documentation of the offshore extent of the sea breeze.

3.6.1 Seasonal variability
The time and direction of the strongest seasonal winds corresponded to the occurrence of summer storms (spring through till autumn, prevalently from the South) and sea breeze (south/southeasterly winds during the afternoon in the summer months). Although the sea breeze is strongest in the summer, it is present all year. This, combined with winter storms, explains the variation of winds in the winter months, which offer a wider component of wind direction, lacking prevailing direction.

Based on the correlation of the wind and current vectors, the highest correlations occur during times of highest wind velocities, as observed during spring and summer months. The correlation magnitude is dependent on the duration of high wind velocities in a consistent direction, implying that less persistent winds, even though of high velocities, will not have as high an impact on the surface currents. The highest correlations are found in the shelf region, where depths did not exceed 150 m. The correlation coefficient immediately north of Rottnest Island was low due to the influence of the island on the flow pattern (wake effect).

Phase shifts between wind and surface currents throughout the seasons also reflected the seasonality of the wind. The Leeuwin Current is strong enough to persist throughout the year, clearly opposing the wind by 180° in the summer and spring months, during which the southerly winds, based on storms and sea breezes, are more common. Throughout these months, the spatial separation between phase shift gradients is strongly linked to the depth of the study area. Shallower regions show lower phase shifts, implying that the more shallow regions react more quickly and
strongly to the wind than the deeper offshore regions. Within the shelf areas, in depths of up to 150 m, the general phase shift agrees with Ekman transport. Further offshore the phase shift is much larger, up to 180°, indicating the Leeuwin Current dominates the flow direction, suppressing the effects of the wind, especially in seasons where the wind opposes the prevailing current. The Leeuwin Current is persistent in its direction, irrespective of the wind direction.

3.6.2 Summer storms:
Summer storms consist of periods of prevalent southerly winds lasting up to 4 days, with speeds up to 25 m/s. Given the current knowledge on the relationship between surface currents and the wind, even in the presence of the Leeuwin Current, one might assume that the surface currents would, at the end of a strong storm, align with the wind in both wind direction and a percentile of the wind velocity. However, based on the examples given of summer storms, it is clear that the response of the currents isn’t as predictable as presumed. Currents in the shelf region reacted more strongly than in the offshore region for both examples, in respect to the direction of flow. This is made apparent in the complex correlation calculations, as the shelf currents show much higher correlation over a 24 h period than the offshore currents. During the 16:00 to 0:00 correlation average, both shelf and offshore currents show near perfect correlations, even though the offshore currents do not follow the direction of the wind. This implies that an increase in velocity of the offshore currents coincides with the increase of the wind velocity, leading to increased correlation on hand of the velocity, not the direction. At times when the southerly winds persist at high speeds, the offshore surface currents show tendencies to follow direction, yet not velocity (Figure 3.7). From this we can conclude, that the response of currents to weak wind velocities (<10 m/s) are higher in shallow areas, whilst strong winds (>10 m/s) can induce stronger current velocities or coinciding current directions even in deeper regions, if persisting over an adequate time period. In example 2, with the increase in velocity of the southbound offshore currents, the build up of an eddy located above the Perth Canyon is promoted. The eddy remains in the same location throughout the duration of the storm, building up as time extends.
With extremely high wind velocities, currents throughout the study site reach above-average velocities. The highest velocities found over the period of the storm, are found in the outskirts of the eddy. The V components of the currents averaged at 2.4% and 1.8% of the wind V components in both summer storms respectively, which, based on previous findings such as by Prandle (1991) and Hammond et al. (1987), is as expected. Currents of high velocities can have large implications on biological, forecasting, and economical factors. Forecasts e.g., for search and rescue, are made based on local currents, and can be significantly altered based on the presence of eddies. Higher velocities will increase the distance travelled in the water, whilst the eddy may completely deter from the originally calculated direction of travel. Knowing when and where to expect an eddy, and the dimensions thereof, is becoming an increasingly important skill and asset; further research will be invested into obtaining more knowledge on eddies in the study site. The eddy found in Examples 1 and 2 were found to stay in place whilst gaining in strength and size, which imposed the notion that it was migrating when focusing on the transect plots (Figures 3.11 and 3.12). The Perth Canyon seems to be a supporting factor in the build up and sustainability of eddies, allowing these to persist over periods up to several weeks (Chapter 4).

### 3.6.3 Winter storms:

Winter storms, consisting mainly of northerly winds, enhance the Leeuwin Current in both velocity and width. The shelf currents tend to follow the general direction of the wind at lower velocities. The higher offshore velocities lead to a delayed reaction in the offshore surface currents when the winter storm winds rotate from northerly to westerly, however the currents follow suit after <3 h, coinciding with the findings of minimal lag. With the lower-velocity currents following the wind pattern more promptly in the shallower areas, the potential for eddy formation could be expected, yet the winter storms have been observed to repeatedly aid in the degradation of eddies in this area.

Variations in patterns of correlation between wind and surface currents, particularly surrounding Rottnest Island, lead to the conclusion that there is no consistent reaction of the currents to the wind based on the bathymetry and geological surroundings. There is a high correlation offshore based on velocity, and high correlation based on direction on the shelf. The currents in the shallow region, which
have less inertia as they have less volume (due to limited depth), imitate the change of direction the wind undergoes throughout the storm events. The V components of the currents winter storm of July 2012 agreed with previous findings, such as by Hammond et al. (1987), in flowing at 1.3% of the wind V components. This is less than overall expected, and can be explained by the frequent change of direction of wind as well as current directions throughout the storm period, as it requires time for currents to build up in one direction after having altered course. Considering the complex correlations of both storms showing high correlations in the shelf region and offshore (Figures 3.23 and 3.24), the surface current results of Example 4 having a low percentage of wind speed velocity is seen as an exception to the rule, and shows that the currents require a minimum amount of persistent wind forcing of 1 h in order for the currents to follow the change in direction of the wind to allow for the high correlation values. In the offshore regions of Example 4, the high correlation of currents to winds (Figure 3.23 and 3.24), reflect the alteration in velocity, not direction, of currents, which were wind-based. Correlations of current direction to wind direction, such as found in Example 3, could have high impacts on the local ecosystem as it shows how highly variable the shelf currents are in winter storm events. Winter storms are commonly linked to high output of the Swan River, which will introduce freshwater with elevated nitrogen and phosphorus (Petrone, 2010), and impacts the local coastal flora and fauna. If there was contaminated water in the outflow, it would be of high importance to be able to anticipate the movement of the surface currents of the shelf region in order to reduce contamination. The findings here suggest that the wind patterns should be consulted before assuming normal seasonal current patterns, as the currents are highly likely to align with the wind.

3.6.4 Sea breeze:
The effects of sea breeze events offshore, were found to exceed the range of the HFR used in this study. Strong reactions were observed to reach 114.2°E. Statements of fishermen feeling the sea breeze offshore, above the Perth Canyon, have been documented (Rennie et al., 2009), yet scientific data supporting these perceived evaluations, are only herein documented.

Sea breeze events have here been proven to have varying effects on surface currents based on their strength and duration. Offshore currents react by altering direction when the wind direction is maintained over a longer period (>6 h), whilst shelf
currents react more promptly to winds. Offshore currents will increase their velocity when the wind picks up, although they may maintain their direction irrespective of the wind direction for some time (<3 h). This agrees with the observations from the winter storms, stating that stronger currents require more time to react to wind forcing than weaker currents. This can allow for the build up of eddies as, with more quickly reacting shelf currents, greater shear is created between the opposing and accelerated currents. Further research will be undertaken to verify the formation of eddies under these circumstances.

Previous findings (Masselink, 1997; Pattiaratchi et al., 1997; Gallop et al., 2012) have shown recurring sea breeze events to be the driving factor for the Capes Current, coinciding with findings here. The maximum current speeds of the northbound shelf currents were found to be up to 2% of the northward wind components, agreeing with observations previously recorded by Hammond et al. (1987). Prandle (1991) found current “slabs” to align with the wind vectors, with variations within these slabs being due to variations in the slabs’ thickness. Findings in this paper coincide with this assumption, and expand it by explaining the variation in thickness of the slabs based on the duration of the wind forcing as well as the location of the slabs, requiring longer wind forcing in offshore regions and shorter in shelf regions to attain the same slab thickness. Findings in this paper agreed with previous observational data as well as modelling results (such as by Orlić et al., 1994; Kovačević et al., 2000; Poulain et al., 2004), in confirming that particular wind events can lead to the reversal of currents over a period of time based on the duration and intensity of the wind event. The reversal of local currents can then, concurring with Poulain (et al., 2001), lead to the formation of mesoscale structures such as eddies, which form based on vorticity given by the shear zone between the opposing currents.

3.7 Concluding remarks
Based on current vector data derived from HFR and meteorological data, surface currents were found to respond to the wind events with velocity increase (offshore and shelf) and/or with change of direction (sometimes lacking offshore). The shelf region showed higher correlations of currents to short-term wind direction changes than offshore currents. Both offshore and shelf currents responded to long-term persistence of wind direction by aligning in direction and gaining velocity in the
same direction. Most significant correlations between the wind and current vectors (as high as 1) were found on the shelf in depths less than 150 m, during periods of strong (>15 m/s), persistent (> 3h) southerly winds, such as sea breeze events and summer storms. These high correlations further documented the positive relation between the southerly winds of the summer and spring months with the Capes Current. Additionally, it was shown that the Leeuwin Current, when the southerly winds and opposing Capes Current were present, is reduced in width as its eastern boundary is forced further offshore, which can lead to an increase in velocity indicating that it does not decrease in volume. This contradicts previous findings (Pearce and Pattiaratchi, 1998), which state that the Leeuwin Current weakens during periods of southerly wind stress, and in future should be considered in e.g. search and rescue or pollutant tracking.

Overall, V components of currents reached an average of 1.3% to 2.4% of wind V components, with the exception of one storm event, during which the currents showed no correlation to the wind, which is explicable by widely scattered maximum current velocity directions. Without the exception, the study aligns with previous findings by Prandle (1991) and Hammond et al. (1987), which state the expected percentage of surface current velocity to be between 1% and 3% of the wind velocity.

Effects of the sea breeze were detected to the furthest western extent of the study site, up to 150 km offshore, creating the most westerly documentation of the Australian sea breeze thus far. The extended range of the sea breeze will impact future hydrological modelling and forecasts effecting e.g. navigation and contamination mitigation, and should lead to further research of the offshore extent of sea breezes on other coasts worldwide.

A region of low correlation was commonly found in the shear zone between the Capes Current and the Leeuwin Current, allowing for clear documentation of the shear zone, which had thus far not been clearly documented. The shear zone, located at 115°E to 115.2°E, can act as a retention zone and should be included in future hydrological and oceanographic calculations and forecasts, e.g. population dynamics, algal bloom distribution, and search and rescue. Furthermore, research should be undertaken to determine the exact role of the shear zone in the formation of eddies in the region.
Chapter 4

The influence of wind events on mesoscale eddy generation on the Rottnest continental shelf, Western Australia

4.1 Summary
Eddies can impact the entire water column and have large effects on the marine ecosystem. They also affect navigation and planning as their velocities often exceed that of the average local current. This chapter aims at determining the response of eddy events to wind events on the continental shelf surrounding Rottnest Island, Western Australia, focusing in particular on the summer months.

Using HFR data, eddies of approximately 60 km in diameter and lasting up to 2 weeks were found to occur regularly during the summer months on the Rottnest continental shelf. The dominant generating mechanism was related to an increased wind-driven velocity shear between the two dominant currents. Southerly winds, generally correlated with summer storms and sea breezes, intensify the northward Capes Current, which increased the shear between the Capes Current and the Leeuwin current. The shear functions as a generating mechanism for anti-clockwise eddies. The Rossby Number of these eddies is Ro~1, indicating a sub-mesoscale eddy. These eddies develop along the water column reaching depths exceeding 200 m and are stationary in the region as they are trapped in the Perth Canyon, which blocks their migration offshore and along-shelf directions.

4.2 Introduction
Surface currents play a critical role in oceanography, controlling the dynamics in biological, physical and chemical fields: changes in cross-shore or along-shore flow
within the surface currents control larval dispersal as they favour or inhibit larval retention (Largier, 2003); surface currents and surface wave-induced mixing determine plume dispersion or blocking (Jones et al., 2008); pollutant tracking, damage control, as well as navigation, depend on surface currents and their spatial and temporal variability. Previous studies, e.g. Zhao et al. (2011) and Kaplan et al. (2005), have described surface currents to be largely wind-driven, especially in coastal zones. Wind-driven surface currents accounted for 67% of the subtidal variability off the coast of California, allowing an estimation of the winds based on the surface currents (Harlan and Georges, 1994). Wind events in WA show major seasonal variations, which, in turn increase variability in surface currents, as shown in previous studies (Chapter 3; Solabarrieta et al., 2015).

Eddies are ubiquitous structures in the global oceans, transporting water properties, such as heat, salt and, carbon, around the ocean, and thus typically introducing different properties to their surroundings. They occur in a range of temporal and spatial dimensions, their diameters ranging from millimeters, to hundreds of kilometers. Small-scale (order of millimeters) eddies are associated with turbulence and typically last a few seconds, whilst the larger features may persist for several months. Those eddies which are between 60 km and 500 km in diameter, and persist for periods of days to months are commonly referred to in oceanography as mesoscale eddies and are a common feature of the west Australian coastline. In these eddies the Coriolis force is dominant and therefore the Rossby number (ratio of the convective to the Coriolis terms in the Navier-Stokes equation), Ro<<1. Smaller scale eddies with diameter less than ~60 km are defined as sub-mesoscale eddies, with Ro~1, and persist for periods of 2 to 3 days. Recent studies have shown that the eddy-induced mass transport, particularly in the sub-tropical regions, may reach 30 Sv to 40 Sv (Sverdrup, 1 Sv = 10⁶ m³/s), comparable to that of the large-scale wind- and thermohaline-driven circulation (Zhang et al., 2014). With vertical velocities up to 100 m/day they are important features for nutrient cycling in the upper ocean (Thomas et al., 2008). Eddies also induce sub-surface flow, which can lead to the vertical displacement of the nutricline and the halocline, and displacement of large quantities of kinetic energy. The mass flow associated with horizontal translation is significant (Flierl et al., 1980) and can impact the biodiversity of the region. Eddies are key determinants of the depth of the mixed layer within the water.
column (Mihanovic et al., 2016; Rao et al., 1989), and can determine upwelling of chlorophyll and nutrients from the deeper oceans (Aristegui et al., 1994). Eddies offer important energy and vorticity balances, describing the character of oceanic general circulation, and cannot be neglected for an accurate understanding of large-ocean scale circulation (Holland and Lin, 1975). It is important to determine when and where recurring eddies appear, as their interaction with ocean currents has significant impacts on the ocean wave fields, with important consequences on navigation, coastal structures, and even beach erosion and sediment transport. Previous findings suggest that eddies form in the lee of islands (Pattiaratchi et al., 1987; Aristegui et al., 1994), or due to outflow of rivers (Zhao et al., 2011). Wind is also known as both an eddy generating and dissipating mechanism (Sentchev et al., 2013; Halverson et al., 2013). Paduan and Cook (1997) determined eddies as mesoscale patterns that evolve with major wind reversals. Wind has a high impact on surface currents at sub-tidal frequencies, such as storms (Zhao et al., 2011), and is hence, in this paper, expected to be the main driver of eddy formation as well as dissipation.

This paper uses ocean surface current data derived from HFR together with meteorological data (wind) and satellite data (sea surface temperature (SST) and ocean colour imagery showing sea surface chlorophyll (SSC) to examine the role of wind forcing on meso- and sub-mesoscale eddies along the Rottnest continental shelf, offshore region of southwest Western Australia. The varying intensities and durations of wind events allow for a comprehensive analysis of the effect of wind on eddies in various scenarios. In particular the following points are addressed:

1. The seasonal pattern of eddies;
2. The response of eddies to specific wind events, deemed representative of seasonal wind patterns, such as those observed during summer storms;
3. An explanation of the potential mechanisms of the origin of the eddies.

This study will offer new insights both into the development and dissipation of eddies as well as their seasonality. This will allow for better understanding of the currents on the continental shelf of Rottnest Island, as well as enforce current knowledge on eddy formation.
The Chapter is arranged as follows: Section 4.3 describes the study area; Section 4.4 describes the data set and the analysis techniques. Results are presented in Section 4.5, Discussion is given in Section 4.6, and concluding remarks and implications of the results are summarized in Section 4.7.

4.3 Study site
The Rottnest continental shelf is located in the southwest of Western Australia, offshore the coast of Perth (Figure 4.1). Ocean circulation in the region is driven by the southbound Leeuwin Current and its counter current system, the Capes Current (Woo and Pattiaratchi, 2008; Figure 4.1).
Figure 4.1: Map of the study site depicting the Capes Current (blue arrows), flowing northwards on the shelf, and the Leeuwin Current (red arrows) flowing further offshore and directed southwards. Locations of current meter moorings are also shown in the map (black squares), along with details of the bathymetry including the Perth Canyon.

The Leeuwin Current carries warm and low salinity (average temperature at surface 20.8°C; average salinity at surface 35.6 PSU) water from the Indonesian Throughflow flowing southward along the edge of the continental shelf of WA (Feng et al., 2003). It is strongest during the austral autumn and winter months (April to September) when the southerly winds opposing the flow direction are weaker (Chapter 3). In contrast, the Capes Current flows equatorward along the Rottnest continental shelf, with higher salinity (35.8 PSU) and lower temperature (~24°C); Pearce and Pattiaratchi, 1999) than the Leeuwin Current. It is generated in the summer months by localized wind-driven upwelling events, and flows on the inner
continental shelf with an extension of approximately 20 km width at 50 m depth (Gersbach et al., 1999). During spring and summer months, the Capes Current intensifies under the action of the southerly winds and simultaneously has an effect on the southerly flow of the Leeuwin Current, altering its velocity and forcing it further offshore (Chapter 3; Pattiaratchi et al., 1997).

The Rottnest continental shelf has a predominant bathymetrical feature known as the Perth Canyon, which drops from the 200 m isobath, west of Rottnest Island, down to 1000 m within only 6.5 km (Figure 4.1). Pygmy blue whales use the canyon as a feeding area in the summer months making it an important ecological and touristic feature of this coast (Rennie, et al., 2006).

Storms in the study region vary seasonally. Winter storms occur on average 3 times in the month of July (Gentilli, 1971) and consist of northerly/northeasterly winds which then alternate to southerly/southwesterly winds over a period of 1 to 5 days. Wind speed can be as high as 20 m/s in both directions during these events. Summer storms are characterized by strong (25 m/s) southerly winds and last typically several days. Additionally, the Perth region is exposed to one of the world’s most energetic sea breeze systems, with southerly daily sea breezes exceeding 10 m/s. For the analyses presented in this paper, specific seasonal wind events have been chosen based on the quality and availability of oceanic surface current data from HFR.

The study region is located in the only high eddy kinetic energy band occurring near the subtropical eastern boundary of the global oceans (Delworth et al., 2011). Many studies, including observational and numerical modelling of mesoscale, ocean eddies have been undertaken in this region, focusing mainly on anti-cyclonic, warm-core eddies (Holland and Lin, 1975; Rennie et al., 2007; Fang and Morrow, 2003; Cresswell and Golding, 1980; Feng et al., 2007; Griffiths and Pearce, 1985; Kennedy Jr., 2002; Morrow et al., 2003; Waite et al., 2007). Documented dominant driving factors for the presence of eddies in the study region are related with Leeuwin Current meanders, its interaction with the shelf topography, bottom shear, or barotropic instability. Previous studies have shown that ocean eddies originate from instabilities within horizontal shear flows (Zhang et al., 2014). Along eastern ocean basins, in the presence of upwelling-favourable winds, numerical modelling studies have shown the evolution of a frontal zone, followed by dynamic instability in the
form of a meandering current, which led to the formation of eddies in the frontal zone (Barth, 1994; Roed and Shi, 1999). Once formed, eddies increased in diameter and were either detached and moved offshore, or remained trapped by the bottom topography and dissipated locally. Instability processes have been identified as most common causes for the onset and growth of mesoscale structures: (1) frontal instability represents the fastest growing mode; (2) conventional baroclinic and mixed-mode of instability, on the opposite, is associated with a slower growing mode (Lee et al., 1991). Focusing on the meanders in the Leeuwin Current system, a mixed-type baroclinic-barotropic eddy formation mechanism was proposed, in which the baroclinic mechanism was observed in origin with a background barotropic signature (Meuleners et al., 2008). Meanders and eddies also form outside the study region in this study, propagate south and break off into the offshore region; as such, different eddy evolutions have potentially large impacts on local flora and fauna. This study site, with its low tidal range, peculiar wind regimes, as well as bathymetrical features, represents an ideal setting to undertake an investigation of the effects of wind on (sub-) mesoscale eddies. In this study it is questioned if the wind-driven shear between the Capes Current and the Leeuwin Current drives the generation of eddies in the region.

4.4 Methods
The study focuses on surface currents obtained from a network of HFR WERA systems, which provides high-quality coverage of this large study site (Figure 2.7). In addition to HFR data, meteorological data (wind speed and direction), sub-surface currents from moored ADCP instruments, sea surface temperature (SST) and sea surface chlorophyll (SSC) data, are used to provide a full description of the current patterns in the area.

4.4.1 Data
Surface currents derived using HFR data were collected along the Rottnest continental shelf region over a 4 year period from March 2010 till March 2014. Surface current data in the region were made available through the Australian Coastal Ocean Radar Network (ACORN) facility, which is part of the Western Australian Integrated Ocean Observation System (WAIMOS). Radar currents were
measured using a phased array WEllen RAdar (WERA) system deployed along the coast. The radar systems transmit a radio signal at the 8.5125 MHz frequency, with a bandwidth of 33 kHz, providing ocean currents with spatial resolution of approximately 5 km. Surface current measurements are based on the determination of the Doppler shift of a signal transmitted towards the ocean from ocean waves (Crombie, 1955). Surface current measurements using HFR systems have been extensively validated in a wide set of operating environments and conditions, proving their reliability and high level of accuracy, and are now widely utilised worldwide (Paduan and Washburn, 2013; Barrick et al., 1977; Hammond et al., 1987; Liu et al., 2007; Chapter 2).

Despite being high-quality data, HFR measurements are discontinuous in time for a number of different reasons, and thus limited the choice of the storm events to three characteristic storms for the summer season. Summer storms were selected based on the intensity of southerly winds (above 25 m/s) and a minimum duration of 48 h. Similar events occurred in four time intervals (11th to 15th December, 2010; 16th to 31st January, 2013; 22nd to 25th of March, 2013; 20th to 27th December, 2013). Other storms with more severe wind conditions occurred during the 4 years of collected data, however they were not included in the analyses as the radar coverage during these events was not adequate to support the following analyses.

Meteorological data were collected at the Rottnest Island weather station (32.0069 °S, 115.5022 °E), 10 km to 30 km from the Perth Canyon sites and 50 km to 60 km from the radar station sites (Figure 1). Wind speed and direction were recorded at a standard height of 10 m above the ground at a 30 min time interval. These were interpolated and re-sampled into hourly-intervals to match as close as possible radar data and avoid temporal biases in the following analyses.

ADCP data were available on the IMOS portal and were collected at the mooring locations WATR20 and WATR50 from water depths of 200 m and 500 m respectively (Figure 2.8).

Sea-Surface Temperature (SST) data were acquired using the AVHRR (Advanced Very High Resolution Radiometer) sensors on board the NOAA polar-orbiting satellites, and were made available through IMOS after processing at the IMOS
Satellite Remote Sensing Facility. Sea-Surface Color (SSC) images were also available from the MODIS sensor on NASA’s Terra and Aqua satellites through the IMOS Satellite Remote Sensing Facility. All depicted data is in AWST.

4.4.2 Analytical techniques

Data were analysed using MATLAB, focusing in particular on the response of sea surface currents and vorticity to various storm conditions in the region. A vector geometry-based eddy detection algorithm (Nencioli et al., 2010) was used to determine the presence of eddies in the surface radar current fields. The algorithm is based on the typical features of the eddy current fields, and included the identification of minimum velocities to be at the eddy centre, and tangential velocities that increase approximately linearly with distance from the centre before reaching a maximum value and then decaying to identify and define the eddy.

Analysis methods also included the calculation of relative vorticity of the HFR surface currents, defined as \( \zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \). The required spatial gradients of velocity were derived by locally least-square fitting in a least-square sense a velocity plane to each HFR grid point using information from surrounding grid points.

Vorticity fields were used to compute the Rossby Numbers, i.e., the ratio between relative and planetary vorticity, as follows:

\[
R_o = \left| \frac{\zeta}{f} \right| = \frac{\text{Relative vorticity}}{\text{Planetary vorticity}}
\]

where the relative vorticity \( \zeta \) is defined as above and the planetary vorticity is the Coriolis parameter \( f = 2\Omega \sin\phi \), where \( \Omega = 7.2921159 \times 10^{-5} \) rad/sec is the angular velocity of Earth. At the latitude of the study site (-32°), the planetary vorticity or Coriolis parameter \( f \) has a typical value of \( f = -7.71 \times 10^{-5} \) (s\(^{-1}\)), corresponding to 22h34\(^{th}\) period.

The zonal components (U, directed East-West) of current vectors from the shelf region and wind data were chosen to track the eddy intensity. Maximum values for current vorticity versus wind U components were plotted, aiming at finding a correlation between the wind intensity and current vorticity. Time series of V
components were plotted over time to show the development of northerly currents in response to southerly winds.

4.5 Results
The first part of the following section describes the seasonal current and vorticity patterns. Attention is then given to summer storm events, in order to determine the relationship between southerly winds and eddy formation.

4.5.1 Seasonal variability and averages
The seasonal current patterns (spring, summer, autumn, and winter) and the corresponding relative vorticity maps for the Rottnest region are presented in Figure 4.2. The seasonal averaged current patterns depict the Leeuwin Current and the Capes Current, and also identify clearly the shear region between them as a strip of strong positive vorticity (illustrated red in Figure 4.2). The shear is particularly strong during spring, summer and autumn months (Figure 4.2) when the Capes Current is well developed, however it is not present during the winter season when the Leeuwin Current dominates. A dipolar structure with positive-negative vorticity is observed during winter in the northwest area of the radar domain. An elongated eddy located ~60 km west-northwest of Rottnest Island is present during spring months, when correlation between wind and surface currents is particularly significant (Chapter 3). During summer season, vorticity is particularly intense in the shear region, implying high potential for eddy formation, however a clear eddy in the mean current system can only be detected during spring season. The lack of visible eddies in the seasonal averages does not necessarily imply that eddies are not formed in this period of the year, but that their lifetime is most likely of the order of days.
4.5.2 Summer storm January 2013

The summer storm events extend between 16th January and 2nd February, 2013. This period was dominated by southerly winds resulting from two summer storms (Figure 4.3). The initial northerly winds (speed up to 16 m/s) were remnants of the tropical cyclone Narelle that hit north of the study region. Southerly winds characteristic of summer storms occurred on January 17th to 18th and from mid-day of the 20th to 22nd of January, 2013 (Figure 4.3). Wind speed increased sharply from 12 m/s to 25 m/s on 17th to 18th January, and from 5 m/s to 21 m/s on 23rd to 24th January, 2013.
Signatures of the land sea breeze cycles were present on the 18th and 19th, with easterly winds in the morning and strong southerly sea breezes (>15 m/s) in the evening, being less energetic in the early hours of the 20th. The storm is followed by sea and land breeze events of varying strengths: between times of southerly winds of 12 m/s to 16 m/s, the 29th January experiences easterly winds (9 m/s), as well as the 31st January, which shows an even stronger easterly wind event (12 m/s) in the early hours of the day and is followed by weaker (9 m/s to 12 m/s) southerly winds (Figure 4.3).

Figure 4.3: Time series of wind speed and Direction from the Rottnest Meteorological station for the period 16th January to 2nd February 2013.

Figure 4.4 shows the complete sequence of daily averaged currents and SST images for the period 16th January to 1st February 2013 and documents the formation and evolution of a mesoscale eddy in the shear region between the Leeuwin Current and the Capes Current in response to the change of wind direction (red arrow in the plots). No eddy structure is present on 16th January, when winds are directed towards land, however it appears on 17th January when northerly winds are present and SST
suggests the presence of the colder waters associated with the Capes Current. The eddy that first forms west of Rottnest Island is initially small (diameter ~10 km), but then increases in size assuming a more elongated shape in the boundary region between the southwards Leeuwin Current and the northwards coastal current. A second eddy-like structure forms and evolves in the northern region of the shear zone as the colder waters reach that area of the radar domain. The complete sequence is as follows: a) a strong southwards current associated with the Leeuwin Current is visible, with easterly currents in the shelf region; b) wind turns to northerly, the northerly Capes Current enters the coastal strip pushing the Leeuwin current offshore, and an eddy starts forming west of Rottnest; c, d, e) the eddy grows, becomes elongated and moves offshore as the Capes currents propagate northwards; a second eddy structure appears to the north; f, g, h) the smaller eddy migrates northward leaving the radar coverage; i, j) the Capes current tends to bifurcate and turn in a southwards direction while the initial small-scale eddy has further increased its dimensions reaching an approximate diameter of 60 km; k) the eddy has migrated further west, restricting the southward flow of the Leeuwin Current and allowing more room for the Capes Current; l, m, n) the southerly winds still push the Capes Current northwards and a clockwise eddy develops in a “mushroom” pattern offshore Guilderton radar station, which further expands offshore (Figure 4.4 o, p) and then dissipates.
Figure 4.4 Sequence of daily-averaged currents and SST images for the period 16th to 31st January 2013, documenting the formation and evolution of a mesoscale eddy in the shear region between the Leeuwin Current and the Capes Current in response to the change of wind direction (red arrow in the plots).
Similar to Figure 4.4 yet offering a broader spatial scale, satellite ocean color maps presented in Figure 4.5 document the presence of a second large-scale eddy structure (not described above) to the north of the area covered by radar current maps and, most important, provide some hint on the role of bottom topography in trapping the mesoscale eddy offshore Rottnest. In detail: a) 25th January: two well established counterclockwise eddies are present; b) 26th January: the northerly counterclockwise eddy looses symmetry and moves north while the southerly counterclockwise eddy builds up; c) 29th January: the northerly counterclockwise eddy has moved further north/north-west, while the southerly counterclockwise eddy seems trapped in the region; d) 30th January: the mushroom pattern is now clearly visible as the eddy pair evolves further and leads to a strong offshore flow of water between them; e) 31st January: the eddy pair is dissipating and the offshore flow has diminished, turning southerly as the Leeuwin Current pushes further onshore again.
Figure 4.5: Sequence of daily-averaged radar current (red arrows), geostrophic currents (black arrows), depth averaged currents from sub-surface currents at the moorings, and SSC data, for the period January 25th to January 31st, documenting the presence and evolution of the mesoscale eddies in the Rottnest shelf region. (Figure credited to IMOS Ocean current - http://oceancurrent.imos.org.au/)
The Hovmoller (time-depth) diagrams of the East-West (U) components of the currents from 0 m to 200 m below the surface (Figure 4.6) suggest that the eddy evolves both in the horizontal and vertical dimension, which in particular extends up to 100 m below the surface. A diurnal fluctuation in water velocity is in fact clearly detectable between 22nd and 30th January.

![Figure 4.6: Hovmoller (time-depth) diagram of U components (measured at the WATR50 mooring), extending from surface to 200 m depth for the time period 16th January to 5th February, 2013, documenting the vertical extent of the eddy along the water column. Note that the top 30m are not quality controlled and are not included in the discussion.](image)

The Rossby number (Ro) can be used to determine the relative weight of the Coriolis force and the vorticity of the eddy at the time of its formation (Figure 4.7) and during its evolution. At its beginning on 17th January, the counterclockwise eddy had O(Ro)~1, indicating a balance between the Coriolis force and the relative vorticity of the eddy at the time of its formation (Figure 4.7). Similar values were also found when the eddy was already formed (Figure 4.8).
Figure 4.7: Daily averaged current map for January 17\textsuperscript{th}, 2013, and corresponding distribution of $Ro$ at the time of the formation. Values for $Ro\sim1$ indicate a balance between Coriolis and centrifugal forces.
Figure 4.8: Same as Figure 4.7, but for 28th January, when the eddy was well formed after the initial spin-up process. Values for $Ro\sim 1$ indicate a balance between Coriolis and centrifugal forces.
Figure 4.9 illustrates how the eddy diameter, defined by the circumference of the ring of the maximum velocity of the eddy, found in the middle of the radius of the eddy, evolved in time. The southerly counterclockwise eddy steadily increased its diameter in the first week, then it maintained its dimensions for a period of 5 days, and finally decreased in diameter throughout the evolution of the summer storm at a similar rate as the increase.

Figure 4.9: Temporal evolution of the diameter of the mesoscale eddy offshore the Rottnest shelf region.
Both wind and current V components show similar patterns throughout the storm period: low speeds in the initial phase, increasing until the 24th January, decreasing till the 28th and then again increasing in magnitude (Figure 4.10). The current velocities only have a small time lag with respect to wind velocities, suggesting that they are strictly correlated.

![Figure 4.10: V components of currents (black, scaled by a factor 10) and wind (red) plotted over time for the period of 16th to 31st January, 2013.](image)

To better understand the response of surface currents (surrounding/containing an eddy) to wind forcing, a time period of 40 h around 27th January is considered, when the counterclockwise eddy is formed and has reached its maximum spatial extension. Since wind direction in this time window is southerly, the zonal (north–south; V) current velocity component only is considered. Figure 4.11 shows the temporal variability of wind speed (red line), currents (blue line), and the corresponding current field vorticity. As already evidenced above, data suggest that the wind-to-
current response is fast and follows to a good extent the wind variability, with increased current vorticity corresponding to increased wind velocities (Figure 4.11).

Figure 4.11: Time series of the V components for wind (red line), current (blue line), and current vorticity (black line). Data have been properly scaled before plotting to improve readability.
Assuming that the wind-to-current response is linear, the regression between wind speed and maximum current vorticity provided a positive relationship (Figure 4.12). The time lag between wind and maximum vorticity is negligible: in fact, correlation and regression parameters at different time lags (1 h; 2 h) were significantly smaller.

Figure 4.12: Scatter plot between wind velocity (N/S being +/-) and maximum current vorticity (black crosses), linear best fit at 0 h time lag (red line) and corresponding equation.
4.5.3 Summer storm March 2013
The second summer storm event considered in this study occurred between 22nd March and 25th March, 2013 (Figure 4.13). The wind conditions before the storm consisted of 10 m/s to 15 m/s southerly winds for the initial 24 h, followed by southeasterly land breeze in the early hours of 21st March; Winds turned into southerlies reaching 17 m/s in the late hours of 21st, and then decreased velocity rotating to easterlies. The storms started approximately mid-day of 22nd with southerly winds up to 14 m/s, and concluded the early hours of 25th March, 2013.

With respect to the case presented in the previous summer storm, the southerly winds blowing before the storm generated the Capes Current and the resulting shear with the Leeuwin Current “preconditioned” the region with two small counterclockwise eddies within the shelf area (Figure 4.14a), and a well-formed clockwise eddy further offshore (Figure 4.14a). While one of the two counter-clockwise eddies does not develop in spite of the current shear, the second, one originally west of Rottnest Island, quickly grows and migrates northwest (Figure 4.14 b, 23rd March), then shifts south as the wind decreases (Figure 4.14 c, 24th March).

![Figure 4.13: Time series of wind speed (continuous line) and Direction (arrows) from the Rottnest meteorological station for the period 20th to 25th March 2013.](image-url)
Figure 4.14: Sequence of daily averaged surface current maps (black arrows) and wind vector (red arrow) for the time period 22\textsuperscript{nd} to 24\textsuperscript{th} March, 2013. The red (blue) dots and contour lines show the centre and the spatial extension of clockwise (counterclockwise) eddies, as identified in the surface current maps.

In addition to the eddy in the Rottnest shelf region, other mesoscale eddies formed north of the area of radar coverage during the storm event. Figure 4.15 clearly documents the presence and the evolution of at least three separate structures (Figure 4.15 a, b) that formed during the storm, and merged after forming one large eddy after the summer storm left the region (Figure 4.15 c).
Figure 4.15: Sequence of daily-averaged radar current (red arrows), geostrophic currents (black arrows), depth-averaged currents from sub-surface currents at the moorings, and SSC data, for the time period of 22nd to 28th March, 2013, showing the presence and the evolution of at least three separate mesoscale structures along the coast of Western Australia.

The Hovmoller (time-depth) diagrams of the east-west (U) components of the currents from 0 m to 200 m shows the vertical extent of the eddy-induced currents along the Rottnest shelf region (Figure 4.16). During this particular storm event (22nd to 24th March 2013), the eddy-induced currents were particularly intense up to 100 m below the surface.
Figure 4.16: Hovmoller (time-depth) diagram of U components (measured at WATR20 mooring), extending from surface down to 200 m depth for the time period 21\textsuperscript{st} March to 5\textsuperscript{th} April, 2013, documenting the vertical extent of the eddy (up to 150 m below the surface) along the water column. Note that the top 30m are not quality controlled and are not included in the discussion.

4.5.4 Summer storm December 2013
The third summer storm considered herein impacted the Rottnest shelf region in the last week of December 2013 and was characterized by two events with southerly winds lasting approximately 30 consecutive hours, with a short break of weak (5 m/s) easterly winds (Figure 4.17). Between 23\textsuperscript{rd} and 25\textsuperscript{th} December, wind speeds exceeded 15 m/s, and after a short easterly break, wind speeds reached 10 m/s. The daily averaged radar current maps (Figure 4.18 a) clearly illustrate the general circulation features typical of this region (the Capes Current, the Leeuwin Current and the shear zone between the two). An eddy formed in the shear zone to the west of Rottnest Island (Figure 4.18 b), which then migrated northwest following the tilt of the shear region while increasing its size (Figure 4.18 c – f). The same eddy migrated south and its symmetry increased after 28\textsuperscript{th} December, then settling above the Perth Canyon (Figure 4.18 g – h). Several small (diameter <5 km) clockwise eddies formed both on the shelf and offshore during this storm period, however they did not developed to a larger size or they had a lifetime of less than 24 h.
Figure 4.17: Wind vectors (arrows) plotted on wind velocity for the time period covering the summer storm of December 2013.

a)
Figure 4.18: Sequence of daily averaged surface current maps (black arrows) and wind vector (red arrow) for the time period 22\textsuperscript{nd} to 29\textsuperscript{th} December, 2013. The red (blue) dots and contour lines show the centre and the spatial extension of clockwise (counterclockwise) eddies, as identified in the surface current maps.

The Hovmoller (time-depth) diagrams of the east-west (U) components of the currents from 0 m to 200 m show the vertical extent of the eddy-induced currents along the Rottnest shelf region. For this particular storm, eddy-induced westward currents extended up to 200 m below the surface, which was the deepest extent of the measurements. When the eddy on the surface dies down, the westward currents beneath the surface also cease (Figure 4.19).
Figure 4.19: Hovmoller (time-depth) diagram of U components (measured at WATR20 mooring), extending from surface up to 200 m depth for the time period 20th to 27th December, 2013, documenting the vertical extent of the eddy (up to 200 m below the surface) along the water column. Note that the top 30m are not quality controlled and are not included in the discussion.

As evidenced in Figure 4.20, wind and currents are highly correlated at no significant time lag; for this specific storm event, currents reached up to 10% of the wind velocity.
Figure 4.20: V components of wind (red) and current (black, magnified by 10) vectors over the time period from 22\textsuperscript{nd} to 29\textsuperscript{th} December, 2013, showing the nearly instantaneous adjustment of current vectors to those of the wind.

4.5.5 Summer storm December 2010
The fourth summer storm considered here extends from 11\textsuperscript{th} December to 14\textsuperscript{th} December, 2010, and occurs between two typical summer breeze conditions that have wind speeds comparable in magnitude to the storm conditions (Figure 4.20). During the storm, strong southerly winds were present, blowing up to 20 m/s from 12\textsuperscript{th} to 14\textsuperscript{th} December, 2010 (Figure 4.21).
Two mesoscale counter-rotating eddies were present in the radar domain at the beginning of the storm period (11\textsuperscript{th} December, 2010 shown in Figure 4.22 a), and a relatively weak northwards flow associated with the Capes Current can be detected in the shelf region. As the storm hit the region, the two eddies detached from the Capes Current (Figure 4.22 b and c) and several counter-rotating, short-lived (duration <24 h), sub-mesoscale (8 km to 12 km diameter) eddies appear in the shelf region (Figure 4.22 c - e).
Figure 4.2: Sequence of daily-averaged currents and SST images for the period 11\textsuperscript{th} to 15\textsuperscript{th} December 2010, documenting the evolution of a dipole eddy structure and the presence of sub-mesoscale eddies in the shelf region.
In order to determine the driving forces of the eddy, Rossby numbers \((Ro)\) were calculated for the initial formation period of the eddy. Typical values were \(O(Ro)\sim 1\), indicating a balance between Coriolis and centrifugal forces (Figure 4.23). A Rossby Number of \(Ro=1\) is found in sub-mesoscale eddies, which typically reach a maximum diameter of 50 km.

Figure 4.23: Daily averaged current map for 12\textsuperscript{th} December, 2010, and corresponding distribution of \(Ro\) at the time of the formation. Values for \(Ro\sim 1\) indicate a balance between Coriolis and centrifugal forces.
The Hovmoller plot of this time period, created from data from the WATR20 mooring, shows very clearly the strong westward movement of water up to 200 m below the surface (Figure 4.24). The eddy and offshore movement of water in this location had been initiated by 11th December and continued below 50 m after 16th December. Diurnal pulses of westward flow (the top 50 m are not considered as they are not quality controlled) are found in the afternoon hours at the surface as well as throughout the entire water column up to 200 m and are related to the sea breeze wind-driven currents.

![Hovmoller plot of U components](image)

Figure 4.24: Hovmoller plot of U components (measured at WATR20) from the surface to 200 m depth over the time period of 11th to 16th December, 2010, visually emphasizing the effect of the eddy up to 200 m beneath the surface by plotting the U components in m/s. Note that the top 50 m are not quality controlled and are not included in the discussion.

### 4.6. Discussion

Using HFR, SST, and meteorological (wind) data, the seasonal circulation features were investigated and four distinct wind events were analyzed to identify their role in generating and dissipating mesoscale eddies in the shear zone between the Capes Current and the Leeuwin Current. The shear zone between the two opposite flows (the Leeuwin Current and the Capes Current) is a prerequisite for the formation of eddies in the Rottnest shelf region. Wind however appears to be the dominant factor in the formation of the eddies. These eddies are prevalently counterclockwise and after their formation tend to grow and remain within the Perth Canyon region. These structures are persistent in time, since they have lifetimes exceeding 24 h, they are
frequent in time, as they are related to the typical storm conditions, and as such they are clearly visible in the seasonal circulation pattern along the Western Australia shelf region.

4.6.1 Seasonal variability
Highest positive vorticity is represented in areas of high shear, which coincides with the build up of the Capes Current during strong southerly winds. As an eddy is visible in the mean of spring currents, it can be assumed that this eddy is commonly present in the months of March to May. These months have also been shown to have the highest correlation between wind and surface currents (Chapter 3), which leads to the conclusion that the eddy is supported by the southerly winds typical of the season. The summer months, although high positive vorticity is present along the shear line between the Leeuwin Current and the Capes Current, and summer was found to have the second highest correlation between wind and currents of all seasons (Chapter 3), do not show an eddy in the mean current vectors. This indicates that only during times of highest correlation between wind and currents are eddies sustained in the region. It is assumed that the eddy is based on the shear created between the wind-driven Capes Current and the Leeuwin Current, and that the lack of eddy in the mean of the summer currents indicates that, whilst eddies are commonly formed during summer storms, it is not common for these to persist longer than the duration of the storm. Sea breeze events also contribute to the shear by enhancing the Capes Current, and are commonly found in spring months, leading to the augmentation of shear and hence the formation of eddies. The presence of negative vorticity in the northwest area of the study site in the spring months, remnant from the strong negative vorticity found at that location in the winter months, might aid in the maintenance of the eddy as it offers potential for an eddy pair to form. The formation of eddy pairs has been documented in previous studies (Feng et al., 2007; Griffiths and Pearce, 1985), none of which assume the Capes Current or wind to be the driving factor of the counterclockwise eddy. Documented eddies in this region have been characterised as extremities of the Leeuwin Current, which break off and migrate westwards (Feng et al., 2003; Rennie et al., 2007; Morrow et al., 2003), yet it can now be said that counterclockwise eddies in this region are driven by horizontal shear between the Leeuwin Current and the Capes Current, and wind stress, rather than baroclinic instability and buoyancy-driven
boundary currents, such as the Leeuwin Current and the Leeuwin Undercurrent (Holland and Lin, 1975; Griffiths and Pearce, 1985).

4.6.2 Summer storm January 2013:
The Leeuwin Current initially shows high velocity and widens its diameter as it flows closer to shore than typical in the summer months. These characteristics can be attributed to the northerly winds and the continental shelf wave due to the remnants of the tropical cyclone Narelle, which impacted this region until 16\textsuperscript{th} January, 2013. The tropical cyclone altered the current field and the shears in this region and played an important role in preconditioning the region for the eddy by enhancing the Leeuwin Current. There is no eddy visible throughout this period of strong northerly winds, indicating that northerly winds are not suited to promote the development of an eddy in this region. On the evening of 16\textsuperscript{th} January the winds turn southerly as a summer storm commences and the currents on the shelf follow suit without lag. It requires only few (<6 h) hours of the wind’s change of direction for the Capes Current to become visible and an eddy to begin to build up in the shear zone between the Leeuwin and the Capes Current in the vicinity of the Perth Canyon. This eddy continues to build and persists until the storm ends and the land breeze-based easterlies elongate the eddy towards the west on 28\textsuperscript{th} January. The diameter of this eddy grows steadily as the southerly winds continue to offer stress to enhance the shelf currents, until a maximum diameter of approximately 60 km is reached before dissipating at a similar pace to its build up. The Rossby Number in the centre of the eddy was found to be in the order of 1, which shows that there is a balance between the Coriolis Force and the relative vorticity in this region, which is typically only found in eddies <50 km in diameter, whilst in larger eddies, such as this one, geostrophic balance is expected where the Coriolis Force dominates. This only feasible if a force, here defined as the wind, enhances the relative vorticity in the eddy. The V components of the currents reaching 10% of the V components of the wind, yet remaining at 5% for the majority of the time, agrees with Afargan (2015), in showing that velocities are enhanced by the presence of an eddy, as currents tend to reach only 3% of wind velocity in absence of an eddy (Chapter 3). This increase in velocity can alter the physical as well as biological characteristics of the coastal region, impacting navigational routes, search and rescue missions, pollutant tracking as well as larval distribution, leading to alterations of the population dynamics in the
which emphasizes the importance of knowledge concerning such features. The time at which the eddy of January 2016 reached its maximum velocity coincided with an increase in symmetry and area, resulting in a more evenly circular eddy rather than the elongated form, which was its original state as it formed in the shear zone between the Capes and the Leeuwin Current. As the eddy widens to gain longitudinal width, the build up of a clockwise eddy directly north of the anticlockwise eddy is facilitated by the shear created by the counterclockwise eddy. The two eddies surmount to an eddy pair, which leads to a strong offshore flow of shelf water. Such offshore flows of shelf water can have large impacts on the flushing of the shelf, which again impacts population genetics of fish in the region, and hence fishing, as well as the tracking of chemical and biological particles. The Hovmoller plot proved the eddy to reach depths of up to 200 m beneath the surface (Figure 4.5). This allows for the Perth Canyon wind-driven eddies to be further confirmed and expanded into the third dimension to include depths of up to 200 m. In reaching such depths, upwelling may be induced. This transports nutrients to the upper layers of the water column and attracts large marine animals such as pygmy blue whales, which again attract tourists and drive ecotourism.

4.6.3 Summer storm March 2013
Although the summer storm of March 2013 was shorter and had comparatively lower wind velocities than other herein selected summer storms, the impacts of the southerly winds were large. They promoted the formation of three billows, which later merged into a single large (diameter >100 km) eddy. Billows, such as were present prior to the storm, have been found and documented in nearly identical locations over the past 20 years (Figure 4.26) and are characteristic for this region. The large eddy was spun up by the storm, which allowed for the billows to join as the shelf currents were enhanced. The combined vorticity resulted in higher velocity and for large quantities of the shelf water, containing nutrients, chlorophyll, plankton, and larvae, to be transported offshore. This will have impacted the ecosystem of the region as areas further offshore gained nutrients and the region north of the eddy was deprived of these. This was enhanced by the offshore movement of water up to 150 m beneath the surface as the eddy grew in both diameter and depth throughout the storm (Figure 4.15). Events like this promote fishing opportunities offshore, particularly in the region of the Perth Canyon, above
which the eddy settled. At the same time, the region north of the eddy may have been deprived of larvae for example, which would have been essential for the next seasons rock lobster harvest (Pearce, 1991). Overall, the build up of the eddy in March 2013 shows that weaker (<20 m/s) southerly winds are sufficient to build up an eddy in the shear zone, approximately above the Perth Canyon, which can have large impacts on the flora and fauna of the region.

Figure 4.26: Satellite images of the study region depicting SSC values, which show billows that occurred in the study region in 1981 (left) and 2002 (right). These strongly resembled the billows, which occurred prior to the eddy of March 2013.

4.6.4 Summer storm December 2013
The shear that was present prior to the summer storm of December 2013 showed potential to form eddies throughout the entire HFR data range, yet it wasn’t until the strong southerly winds of the summer storm commenced, that an eddy actually formed and exceeded a diameter of 4 km. This confirms that, although there is horizontal shear present between the currents, it is the additional enhancement of the Capes Current via persistent (>24 h) southerly winds, which lead to the formation of mesoscale eddies. The eddy, although it had initially formed north of the Perth
Canyon, migrated south and settled over the Perth Canyon before migrating slightly further offshore in order to allow for the expansion of the eddy further into the third dimension. The Perth Canyon appears to capture eddies until they exceed the diameter (and depth) of the canyon and eventually dissipate or, as in this case, migrate offshore before dissipating. As the eddy migrates offshore, it transports large amounts of shelf water to the offshore region. The effects of the eddy, as well as its migration, were visible up to 200 m beneath the surface (Figure 4.19). The westward movement of water was visible at 200 m after the eddy had migrated westwards on the surface, supporting the theory that eddies become trapped in the Perth Canyon as they reach depths greater than offered by the surrounding bathymetry. Nutrient-rich water, which is brought up from the Canyon by upwelling within the eddy, can enhance the fishing potential and increase fisheries take allowances, which will promote local fisheries and economics.

4.6.5 Summer storm December 2010:
During the days prior to this summer storm, the sea breeze patterns showed no effect on the currents in respect to the build up of an eddy. After a mere 20 h of southerly winds due to the storm however, an eddy is clearly visible above the Perth Canyon. This eddy persists and builds until the storm dies down and the winds return to the diurnal sea breeze pattern. When looking several days past the storm event, it can be seen that there is no eddy in the area. This confirms that it wasn’t masked by the easterly winds causing westerly surface currents, but completely dissipated after the southerly winds died down. A diurnal pulsation of the westward currents was found in the afternoon hours at the surface as well as up to 200 m beneath the surface (Figure 2.24), which is generally when the southerly winds are enhanced by the local sea breeze. It is concluded, based on a Rossby Number of ~1 and observations of reactions of the currents to this wind event, that it is solely the southerly winds that offer the particular wind stress required to enforce the Capes Current sufficiently to provide adequate horizontal shear for the formation of an anticlockwise eddy in this region to occur. After a clockwise eddy forms in the northern region of the study site, the two eddies form a mushroom pattern, which provides a strong offshore movement of shelf water. The offshore transport is detrimental to larvae and nutrients, which were destined for the northern shelf region of the Rottnest
continental shelf, and has a significant impact on search and rescue missions as well as navigational planning.

4.7 Concluding remarks
Using HFR data, SST and SSC data, and meteorological data over a period of 4 years, the climatology of eddies on the Rottnest continental shelf has been examined. Counterclockwise eddies have been found to form during summer storm events and are visible in the spring seasonal mean, coinciding with times of strong southerly winds and high wind-current correlation. The seasonal variation in vorticity can be deduced to the seasonal variation in wind, which leads to seasonal variation in the local current system. Persistent eddies form when large shear between the Leeuwin and the Capes Current is present, occurring when southerly wind offers sufficient surface stress for the Capes Current to flow strongly. The counterclockwise eddies tended to settle in the Perth Canyon, where they were found to extend to 200 m beneath the surface. Clockwise eddies, found in the northeast of the study region, complete an eddy pair with the counterclockwise eddies. The clockwise eddies are spun up by the counterclockwise eddies after being initiated as a meander in the Leeuwin Current (as found by Feng et al., 2007; Waite et al., 2007), which then collides with the counterclockwise eddy. The eddy pair forms a mushroom pattern which leads to strong offshore flow of the shelf water, extracting nutrients from the shelf region and inhibiting these to travel further north than 31.5°S. The Capes Current combined with Ekman transport have previously been found to lead to the flushing of the shelf up to 9 times a year (Gersbach et al., 1999). The influence of eddy pairs has now been proven to additionally contribute to this phenomenon. As the Capes Current is a major mode of transportation for larvae along the coast, this may impact the distribution of fish and shellfish populations (Pearce, 1991), which should be considered in future implementations of fishing zones.
Chapter 5

Analysis of surface current patterns along the Turquoise continental shelf Western Australia

5.1. Summary
HFR current measurements acquired using CODAR SeaSonde system along the WA coastline were used to investigate dynamics of the surface circulation along the Turquoise continental shelf over a 12 month period extending from January to December 2013. HFR data identified the presence of a large-scale, cold core, clockwise eddy at approximately 114°E, -31.5°S in March and August, weaker and further southeast in the months between, visible in seasonal averages of winter and autumn. This mesoscale eddy is a stable and persistent feature, which is found in the region during ¾ of the year. Monthly and seasonal averaged current maps show that this eddy is associated with an eastward meander of the Leeuwin Current. This meander can inhibit the northward flow of the Capes Current even in months of strong southerly winds when wind forcing has been found capable of reversing the dominant flow in the offshore region and intensifying the northwards current in the shallower shelf region. On the other hand, when the mesoscale eddy was not detected within the shelf region, the Capes Current was clearly identified at its northernmost extent of 30°S. The mesoscale eddy forms mostly during wind reversals, such as those typically occurring in the winter months. This eddy is of particular interest in the region as strong coastal upwelling occurs during winter months when this mesoscale feature is most common. The eddy isolates cold, nutrient rich waters originating from coastal upwelling.

5.2. Introduction
Surface currents have been proven to play significant roles in population genetics of species (Largier, 2003), impacting fisheries and fishing regulations, plume dispersion
(Jones et al., 2008), navigation and route planning, search and rescue operations, spill tracking and containment, as well as debris and pollutant tracking. Research has shown surface currents to be primarily wind-driven (Zhao et al., 2011; Chapter 3). Major wind forcing events, primarily consisting of southerly winds, along the Rottnest continental shelf of Western Australia (south of the study site) have been defined as sea breeze events and summer storms (Chapter 3; Chapter 4).

In recent years, a significant amount of studies have focused on the Rottnest continental shelf region, located off the coast of Perth, Western Australia, in particular on the climatology of currents in this region (Cresswell and Golding, 1980; Cresswell, 2009; Feng et al., 2003; Godfrey and Ridgway, 1985; Kennedy Jr, 2002; Legeckis and Cresswell, 1981; Pearce and Griffths, 1991; Rennie et al., 2009; Rennie et al., 2006; Smith et al., 1991; Woo and Pattiaratchi, 2008; Zaker et al., 2007). One of the most significant outcomes of this intense investigation within the last ~16 years was the Capes Current system and its meridional extension spanning cape to cape during the austral summer months. However, the sparseness in temporal and spatial dimensions of observations in areas further north, such as the addressed study site, prevented from a detailed analysis of the exact northwards extension of this peculiar current feature.

Locally, the throughflow of currents is driven by the southbound Leeuwin Current and the seasonal northbound Capes Current (Figure 5.1). The Leeuwin Current has been well researched (Feng et al., 2003; Godfrey and Ridgway, 1985; Kennedy Jr, 2002; Pearce and Griffths, 1991; Smith et al., 1991; Waite et al., 2007; Caputi et al., 1996) and is acknowledged as the dominant oceanographic feature off Western Australia, commonly featuring meanders and undulations (Figure 5.2), which can lead to large offshore eddies (Figure 5.3). It is a warm, low salinity current which flows along the coast in the winter months, its eastern boundary getting pushed further offshore in the summer months when the Capes Current is present (Chapter 3; Pearce and Pattiaratchi, 1999). Although directed against the prevailing wind direction during spring, summer, and autumn months, it is a persistent feature at depths up to 250 m depth centered at 100 km offshore throughout the entire year with the exception of January (Smith et al., 1991). Pearce and Pattiaratchi (1999) suggested that the intensification of the Capes Current in January, due to seasonally
strong southerly winds, may delay or slow down the Leeuwin Current during this month. However, more recent results show strong southerly wind events to intensify the Capes Current mean speed and width, thus pushing the Leeuwin Current further offshore, occasionally leading to the increase in velocity of the Leeuwin Current as its diameter declines (Chapter 3). From an ecological point of view, the Leeuwin Current and the Capes Current have significant effects: the first is considered a major driving factor for species distribution along the coast (Caputi et al., 1996), while the second controls the flushing of the upper continental shelf up to 9 times per annum (Gersbach et al., 1999). The displacement of the Leeuwin Current due to the increase in flow of the Capes Current, may mean that the Capes Current, has large implications on the distribution of species in the shelf region along the coast of WA and may impact fisheries and regulations. The interaction between the two major currents generates eddies in the shear zone between the two streams. Rennie et al. (2009) showed the importance of upwelling events in the Perth Canyon on pelagic production and physical aggregation of plankton, which in turn attract whales. Similar events (i.e., eddy-based upwelling or other mesoscale current formations) have not been documented further north along the coast.
Figure 5.1: Schematic of the currents impacting the waters along the West Australian coast, including the Leeuwin Current, and the Capes Current (in the austral summer months). The area of the SeaSonde coverage over the Turquoise continental shelf between Jurien Bay and Fremantle is shown as a red box.
Figure 5.2: Classification of the observed meso-scale features of the Leeuwin Current showing the progression of the flow from a jet along the shelf break (dashed line) through to a meander which detaches into an anti-clockwise eddy (from Pearce et al., 1991).
Figure 5.3: Classification of the observed meso-scale features of the Leeuwin Current showing the progression of the flow from a jet along the shelf break (dashed line) through to a meander which detaches into an anti-clockwise eddy (images from IMOS ocean current: http://oceancurrent.imos.org.au/).

High-Frequency radar (HFR) systems are routinely employed to measure surface currents in the shelf and offshore regions at distances of up to 200 km offshore. Since the early studies from Crombie (1955) and the developments by Barrick (1972; 1978; Barrick et al., 1974), HFR have been applied in different coastal regions to resolve the temporal and spatial scales of motion of surface currents, in particular to study wind-driven currents (Kim et al., 2009a; Kohut et al., 2006; Kosro, 2005; Paduan and Rosenfeld, 1996), or the Ekman response of the upper ocean (Zelenke, 2005; Zhao et al., 2011; Son et al., 2007; Yoshikawa and Masuda, 2009; Yoshikawa et al., 2007).

The current study uses surface current data from HFR installed along the coast of Western Australia, covering the Turquoise continental shelf, to examine the seasonal variability of surface currents. The Turquoise continental shelf is located approximately 100 km north of the Rottnest continental shelf region. The data set is
ideal to extend our knowledge of the mesoscale seasonal current patterns in this region, in particular regarding:

(1) The seasonal variability of the surface currents, both on the shelf and offshore;

(2) The northern extent of the Capes Current;

(3) The mean state of the Leeuwin Current.

This Chapter is organized as follows: Section 5.3 describes the methods of data and analytical techniques. The results of monthly, seasonal and specific eddy events are featured in Section 5.4 and are discussed in Section 5.5. A general conclusion is then given in Section 5.6.

5.3. Methods and data
HFR data offers high quality, detailed spatial and temporal coverage of this large study site and was hence selected for the analysis of the surface currents within the study region. How and when the data was collected, followed by how it was analysed, is described below.

5.3.1 Data:
Surface current data of the study region were made available through the Australian Coastal Ocean Radar Network (ACORN) facility, which is part of the Western Australian Integrated Ocean Observation System (WAIMOS). WAIMOS is part of the Integrated Ocean Observation System (IMOS), which is a national collaborative research infrastructure, supported by Australian Government. IMOS is led by the University of Tasmania in partnership with the Australian Marine & Climate Science Community. Radar currents were measured using SeaSonde HFR system, which is non-invasive, environmentally friendly, and shore-based. The system is composed of two separate elements, one for transmitting and the second for receiving. The two elements are spaced at approximately 30 m and have an operating frequency of 5 MHz. Surface current measurements are based on detecting the Doppler shift of the Bragg scattering of the electromagnetic radiation over a rough sea (Crombie, 1955). Surface current measurements using HFR systems have been proven to offer a high level of accuracy and have been widely utilised worldwide (Paduan and Washburn, 2013) after having been initiated over 30 years ago (Barrick et al., 1977; Hammond
et al., 1987; Liu et al., 2007). Additional HFR data from WERA (derived as explained in Chapter 3 and 4) is applied to allow the description of the currents in the Rottnest continental shelf region when applicable.

Meteorological data were collected at the Rottnest Island weather station (32.0069 °S, 115.5022 °E; Figure 5.1). Wind speed and direction were recorded at a height of 10 m above the ground (43.1 m above sea level), every 30 min. These were interpolated and re-sampled into 1 h intervals to correspond with radar data. All depicted data is in AWST.

5.3.2 Analytical techniques:
Data were loaded and analysed using MATLAB, focusing in particular on the seasonal patterns of sea surface currents and the corresponding current vorticity. The data set covers year 2013. Though small in absolute values, tidal currents were removed from the surface currents, and the remaining portion was used to investigate the wind-induced surface currents. Monthly averages were produced, allowing for the determination of current patterns in the region, focusing on the northern boundary of the Capes Current and the occurrence of mesoscale structures.

Finally, seasonal (spring: March to May; summer: June to August; autumn: September to November; winter: December to February) averages of sea surface temperature (SST) and current vectors were calculated and plotted using the 2013 data set.

5.4 Results
Based on HFR and SST data, this section documents the monthly evolution and seasonal characteristics of the currents found on the Turquoise continental shelf.

5.4.1 Monthly and seasonal currents
Monthly averaged current maps provide detail on the Capes Current and the Leeuwin Current, showing the northern threshold of the Capes Current to extend past the limits of the data coverage (30°S) during the months of November through till March. During these months the Leeuwin Current flows strongly along a moderately direct north-south trajectory along 114°E to 114°20’E. March to August show a clockwise eddy in the southwest region of the study site, ranging from 10 km to 100 km in diameter, which forces the Leeuwin Current slightly eastward. Due to positive
vorticity (counterclockwise movement) in the mid-northern region of the study site, the months of January through till June show an “S” shape meander of the Leeuwin Current as it diverts away from the coast before protruding onto the coast at approximately 31°20’S and diverting offshore again at 31°40’S (Figure 5.4). Figure 5.2 depicts monthly averages as follows: a) January: northbound Capes Current is present on the shelf, southbound Leeuwin Current is visible further offshore, with a strong shear zone in between the opposing currents; b) February: the Leeuwin Current has increased in width whilst showing westerly tendencies below 31°S; the Capes Current is flowing strongly in the shelf region; c) March: the Capes and the Leeuwin Current are flowing strongly; a clockwise eddy has formed in the southwest region of the study site; d) April: the velocity of the currents of the northerly study region has declined; the Leeuwin Current flows strongly eastward (at 31°S) before turning back offshore and heading west (at 31°40’S); e) May: with a counterclockwise eddy present in the north and a clockwise eddy in the south, the Leeuwin Current clearly follows the “S” shape; f) June: the “S” pattern of the Leeuwin Current has intensified; g) July: while the north-eastern region of the study site depicts strong northerly/easterly currents, the shelf currents and the southern region of the study field follow the “S” pattern; h) August: the northern offshore currents are flowing north, the shelf currents south, while the southern part of the study site is dominated by a clockwise eddy; i) September: the shelf currents are weaker than the offshore currents, which are flowing south/southeast, onto the shelf; j) October: high vorticity, with currents flowing south both on the shelf and offshore, is found in the northern to mid region of the study site. A calm area is found at approximately 30°30’S and 114°10’E, with large potential for a clockwise eddy at its centre; k) November: Capes Current and Leeuwin Current are present with a shear zone in between; l) December: Capes Current has increased its diameter, the Leeuwin Current has increased in velocity.
Figure 5.4: Monthly averages of surface currents from HFR data in 2013, red arrow emphasizes the general pattern of southbound through flow, driven by the Leeuwin Current.
Current vector maps, including both WERA and CODAR data, overlaying SST values, show the continuation of the Leeuwin Current through both radar regions in all seasons, even in those during which the CODAR data shows the “S” pattern in the Leeuwin Current (Figure 5.3). The Capes Current is clearly visible in both radar sets in summer and autumn, only in the WERA in spring, and not at all in winter. Using SST data, the Leeuwin Current can be seen to protrude further east in the winter and autumn months. In all seasons clear mixing of the cold and warm currents can be seen in the shear zone. This is depicted in Figure 5.5 in detail: a) Spring: Leeuwin Current flows strongly with a slight “S” bend where it approaches the coast. The Capes Current is not clearly visible in the CODAR data, yet flows strongly along the shelf in the southern data region, where an eddy is visible; b) Summer: strong Leeuwin Current and Capes Current present throughout the entire region with a slight westward veering of the Leeuwin Current in the area of overlapping data; c) Autumn: Leeuwin Current flows strongly along the “S” trajectory, a clockwise eddy in the southwestern region of the CODAR data enhances this pattern. The Capes Current is present yet flows with less velocity; d) Winter: the clockwise eddy in the southwest region of the CODAR data has further developed, the north-western region shows potential for a counterclockwise eddy to form. Southerly currents are visible on the shelf in both data sets.
Figure 5.5: Seasonal averages of surface current vectors (CODAR black, WERA red) overlaid upon SST values, showing the variation in the width and strength of the Leeuwin Current.
5.4.2 Eddy event
Mesoscale eddies are common features in the coastal region of WA, and their presence is often associated with an “S”-shaped meander in the surface current field. They occur mostly during times of wind reversals, as clearly evidenced during May 2013.

The wind vectors undertook several reversals throughout the period of 17th to 18th May, 2013. Beginning with southwesterly on 17th May, changing to northerly on the 19th and back to southeasterly winds on the 20th, the pattern continues to rotate between northerly and easterly winds before turning westerly by 24th May (Figure 5.6).

Figure 5.6: wind vectors (arrows) plotted on wind velocity (m/s) for the period of 17th to 24th May, 2013.

Current plots depict the development of the eddy, which was not yet established on 17th May, 2013 (Figure 5.7). By 18th May the eddy is clearly visible in the southeastern region of the study site and further develops until 22nd May, with a slight obscurity on 19th May. The “S”-like meandering structure is clearly visible in the flow pattern when the clockwise eddy is present as the Leeuwin Current follows the eddy from the northern end into the shelf region and offshore again on the southern end of the eddy. During the spring time period the shelf currents lack unity in their flow direction and the Capes Current is not apparent. The detailed evolution of the eddy throughout this event is shown in Figure 5.5: a) 17th May: offshore currents don’t show unity in their direction, the shelf currents flow mainly southward; b) 18th May: a clockwise eddy has begun to form in the southeastern region of the study site, the shelf currents flow mainly southward; c) 19th May: the “S” pattern is clearly visible as the eddy has further developed and elongated slightly in the northwest/southeast direction; d) 20th May: the clockwise eddy is still present,
the northern edge of the eddy shows increased velocity; e) 21st May: the eddy has further elongated, forcing the westward bend of the “S” shape further south and out of the region of radar data; f) 22nd May: the eddy has increased in symmetry and enforces the “S” pattern within the radar data range.
5.5. Discussion

An “S” meandering flow pattern of the southbound Leeuwin Current, commonly including a large clockwise eddy located offshore on the Turquoise continental shelf, has been detected in time spans of days, months, and seasons. An example of eddy build up given in May 2013 depicts clearly how the eddy builds up during a period of wind reversals, with no predominant wind direction. The eddy builds up and offers potential for a counterclockwise eddy to develop north of the clockwise eddy, forming an eddy pair. The distinct formation of the counterclockwise eddy is only visible in the monthly average, indicating that it formed later in the month when the clockwise eddy had further developed. The relevance of monthly averages over seasonal averages lies in the capability of these to depict the frequency of short-lived (O(weeks)) events with higher accuracy. May, for example, clearly shows the “S” flow pattern and, in comparison to the eddy event described, also shows a counterclockwise eddy in the northern region of the study site (Figure 5.4 e). Six of
twelve months (January to June) show the “S” flow pattern, April only depicting the southern half of the “S”. July and August show a large detour of the Leeuwin Current as northerly currents rein the northern region of the study site. The winter average explains this in a larger picture as a counterclockwise eddy is visible in the northwestern area of the study site. The SST data shows that the majority of the Leeuwin Current still follows the “S” pattern and does not flow onto the shelf in the northern part of the study site. Traces of the Capes Current, characterized by northerly flow of cooler water (about 0.5°C cooler than the Leeuwin Current in this region) on the shelf, were documented in both the SST data as well as the velocity plots. This lead to shear, building positive vorticity in the region between the Capes Current and the Leeuwin Current (established in Chapter 4), which was found throughout the entire study region, its northern most peak at 29°50’S. The Capes Current is enhanced by strong southerly winds, which characterize the summer and spring months (Chapter 3). Highest correlations between the wind and the shelf currents were found to be in spring (Chapter 3), which again represent months of the strongest Capes Current flow. As November is the only month of spring during which the Capes Current reaches the study site, the northward movement of water is not detectable in the spring average. The Leeuwin Current is said to have the largest impact on larvae distribution and population genetics in the region (Caputi et al., 1996), yet the flora and fauna on the shelf is directly impacted by the opposing Capes Current, which should be considered more significant in the distribution of larvae along the coast in the summer months. With the confirmation of the northern boundary of the Capes Current, bearing cooler, more nutrient rich water (Gersbach et al., 1999), in December and November, alterations in the assumed distribution of species such as rock lobsters, a commercially valuable species for WA, may be necessary. Larval distribution is also effected by retention zones, such as eddies (Largier, 2003). Previous findings (Chapter 4) have shown the summer months to be most likely to display southerly wind-driven eddy formation on the Rottnest continental shelf, whereas the patterns of the Turquoise continental shelf show seasons with common wind reversals, predominantly the winter months, to be more prone to eddy formation. A weak counterclockwise eddy is formed in the summer months in the northeast region of the study site, which pairs up with a clockwise eddy in the southwest area of the study site. The counterclockwise eddy is a result of
the remainder of energy contained by the Capes Current, dissipating simultaneously to the Capes Current. It prohibits the northward flow of nutrients, larva and plankton further north than 30°S on an annual basis, forming a critical boundary for population genetics.

The clockwise eddy increases diameter, peaking in the autumn and winter, and dissipating entirely in the spring and summer. It moves south with the Leeuwin Current over its duration, pushing the Leeuwin Current further onshore as it commandeers a large proportion of the study area, flooding it with open ocean water. The lack of significant bathymetrical variation in the region allows for the migration of the eddy, the transfer of nutrients, plankton and larvae with it, impacting the local flora and fauna. Documentation of recurring eddies further south along the coast (~32°S) showed less migration, as these were trapped/enhanced by the Perth Canyon, a large bathymetrical dip in the Rottnest continental shelf region (Chapter 4). The lack of eddy formation in the spring in this study site implies that, without bathymetrical enticement, shear and single-direction wind stress are not enough to support the formation of counterclockwise eddies. Opposite of persistent southerly winds, it is wind reversals, which allow for the build up of clockwise eddies in the open water of the offshore region of the study site. Many studies on warm-core eddies have been undertaken, characterising the eddies as meander-based formations of the Leeuwin Current (Cresswell and Golding, 1980; Kennedy Jr, 2002; Waite et al., 2007; Rennie et al., 2007; Fang and Morrow, 2003; Feng et al., 2007; Griffiths and Pearce, 1985; Morrow et al., 2003; Holland and Lin, 1975). This study adds to the documentation of eddies in the coastal region of Western Australia by adding a clockwise, large-scale (~100 km diameter), wind-reversal-driven eddy, which has been recorded in the months of all seasons, leading to a large “S” shaped diversion of the Leeuwin Current.

5.6. Concluding remarks
Eddies in this region are largely clockwise and driven by wind reversals. An eddy is present at approximately 114°E, -31.5°S for 6 months and does not break off of the Leeuwin Current, but stays put, migrating slightly southward. This eddy forces the Leeuwin Current onto the shelf region, restricting the flow of the Capes Current, which is rarely visible in months when the clockwise eddy is present. This eddy commences as a meander of the Leeuwin Current, yet is enhanced and sustained by
wind reversals and would not persist without these. This further confirms precious findings (Chapter 4) in the confirmation that eddies in the region of the coast of Western Australia are mainly wind-driven features. At times of strong southerly winds and lack of the clockwise eddy, the Capes Current reaches its most northern extent at 29°50’S. Further research should be undertaken to further confirm the relation between wind patterns and eddies in the study region, upon which the “S” pattern should be included in future schematic mappings of the Leeuwin Current.
Chapter 6

General discussion

This Chapter discusses the overall findings on the circulation of surface currents off the coast of Western Australia, from the Rottnest continental shelf to the Turquoise continental shelf. The first Section (6.1) summarises the original contribution of the research, followed by Section 6.2 discussing the implications of the key findings. Further research to follow up on key findings is recommended in Section 6.3. Section 6.4 gives a general conclusion of the research performed in this study.

6.1 Original contribution
While to date the local currents on the Rottnest continental shelf and the sea breeze of the region has been well researched and documented, the correlation between wind events, such as the sea breeze and the surface currents of the region, had not been. The study region offers an exceptional setting to undertake the study of current-wind correlation as it offers low tide and wave energy regime with incomparably strong and frequent sea breeze events. The bathymetry also sets a unique characteristic, offering the chance to compare the effects of the Perth Canyon on current behavior to that of an average coastline with a steady slope. With the observations, analysis, and conclusions drawn from this study site, a more clear characterization of the response of surface currents and mesoscale features such as eddies, to the varying wind regimes as well as bathymetrical effects was possible. Previously undocumented effects of the sea breeze on offshore currents were described, eddy formations of new characteristics were determined, and the most northern reach of the Capes Current was defined. These, along with their implications, are found in their respective section below.
6.2 Implications of key findings
The work presented in this thesis extends the overall understanding of surface current movements, the formation of eddies, and the seasonal pattern of the eastern boundary current of the southern Indian Ocean, the Leeuwin Current. Combined with previous findings of eddy characteristics and boundary currents, this thesis broadens the overall understandings of oceanic current systems.

6.2.1 Wind-current correlations
The effects of southerly winds were found to have positive correlation on large areas of the Rottnest continental shelf. These were not limited to the Capes Current, but extended to the Leeuwin Current as its velocity was affected by high wind velocity, while usually maintaining an opposing direction to the wind. A contradiction to previous studies, such as by Pearce and Pattiaratchi (1998), which had found the Leeuwin Current to slow down during the summer months when the southerly winds increase in frequency and velocity, was found in the documentation of velocity increase of the Leeuwin Current (southerly flow) during strong southerly wind events. The reaction of the currents to the sea breeze, which were detected up to 150 km offshore, mark the furthest offshore extent of sea breeze documentation thus far. Implications of strong sea breezes this far offshore should be taken into account when planning offshore structures such as oil platforms, as intensified currents may occur, implying stronger than predicted stresses on the structures. The effects of the sea breeze may also impact search and rescue or contaminant tracking offshore, and should be recognized as an important factor when modelling not only shelf, but also offshore currents.

6.2.2 Eddy occurrences
Eddies in the region of the study site had thus far been largely attributed to meanders of the Leeuwin Current (Rennie et al., 2007; Fang and Morrow, 2003; Cresswell and Golding, 1980; Feng et al., 2007; Griffiths and Pearce, 1985; Kennedy Jr, 2002; Morrow et al., 2003; Holland and Lin, 1975; Waite et al., 2007). Findings in this study however have documented a high number of counterclockwise eddies on the Rottnest continental shelf to be wind-based shear-driven eddies, formed between the Leeuwin Current and the Capes Current. These counterclockwise eddies settled in the region of the Perth Canyon until they either dissipated or outgrew the Canyon and migrated west before dissipating. The counterclockwise eddies were found to be
spun up by southerly winds, which prevail in the summer, whereas wind reversals, such as found during winter storms, lead to their dissipation. As the counterclockwise eddies did not migrate and were formed closer to shore, it can be said that the bathymetry had a large impact on the formation of these eddies. The Perth Canyon offers ground for an eddy to develop and spin up the shallow shelf region and simultaneously allows for the southbound flow in the deeper region. This explains why wind of southerly prevailing direction would spin up a counterclockwise eddy in this area.

In the Turquoise continental shelf region, clockwise eddies formed and migrated eastward, not breaking off of the Leeuwin Current. These eddies were spun up by seasonal winds, concurring in their seasonality as they were built up by wind reversals and prevailed in the winter months. The clockwise eddy was dissipated by southerly prevailing winds such as found in the summer months, the only season it was not present in the study site. It was located in depths great enough to have no impact on the surface currents, and hence did not prefer to spin up one side faster than the other during periods of one prevailing wind direction.

Overall this concludes that the formation of eddies is enhanced by wind reversals in areas of deep water, and by wind events of one prevailing direction in areas of canyons and irregularly shaped coastal bathymetry.

**6.2.3 The currents of the Turquoise continental shelf region**

The Leeuwin Current is the dominant feature in this region. Due to a clockwise eddy located at 114°E, -31.5°S, which was present for 3/4 of the year, the Leeuwin Current was found to be pushed further onshore. This forced the Leeuwin Current to increase in velocity as its width had been reduced. This eddy led to the Leeuwin Current being forced onto the shelf, which could lead to upwelling, which would offer new nutrients to the region, impacting the local fishing industry. The Capes Current was documented to its most northern extent (by physical current measurements) at -30°S in November and December, during which the southerly winds prevailed, enhancing the Capes Current flow. This may impact the distribution of commercially fished species and should hence be taken into account when enforcing fishing zones.
6.3 Further research/future work
Further analysis of the Turquoise continental shelf region data is suggested in order to extend the research performed in this study and confirm the occurrence of eddies in the region. Overall the research could be extended to include effects of El Nino and La Nina in the region. Currently ongoing research includes auto-detection of eddies within the HFR data, which will allow for the description of the climatology of eddies in the region. The developed methods of analysis in this thesis could be further applied to other HFR data sets, allowing for the documentation of further current developments and eddy formations. This will facilitate the approach to predicting eddies in the region as well as globally.

6.4 General conclusion
The overall aim of this thesis was to gain a better understanding of the annual and seasonal effects of wind on surface currents and mesoscale formations. This was achieved by analyzing HFR data, collected over a period of 4 years, in the coastal region of southwestern Western Australia. Overall the findings highlighted new conclusions regarding the extent of the effect of the sea breeze off the coast, its impacts on eddy formation and dissipation depending on the bathymetry, as well as its contribution to the most northern extent of the Capes Current. The effects of wind reversals compared to wind events of one prevailing direction on mesoscale features were analysed and lead to the conclusion that the response of the currents is dependent on factors such as bathymetry and shear. Regionally, new documentations of Leeuwin Current patterns and eddy formations were made, leading to suggestions of precaution for offshore construction, as well as new aspects of population distribution along the coast.
Bibliography


